La fisica delle astroparticelle e l'esperimento AMS-02 sulla ISS

CERN Teacher Programme
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Sonia Natale

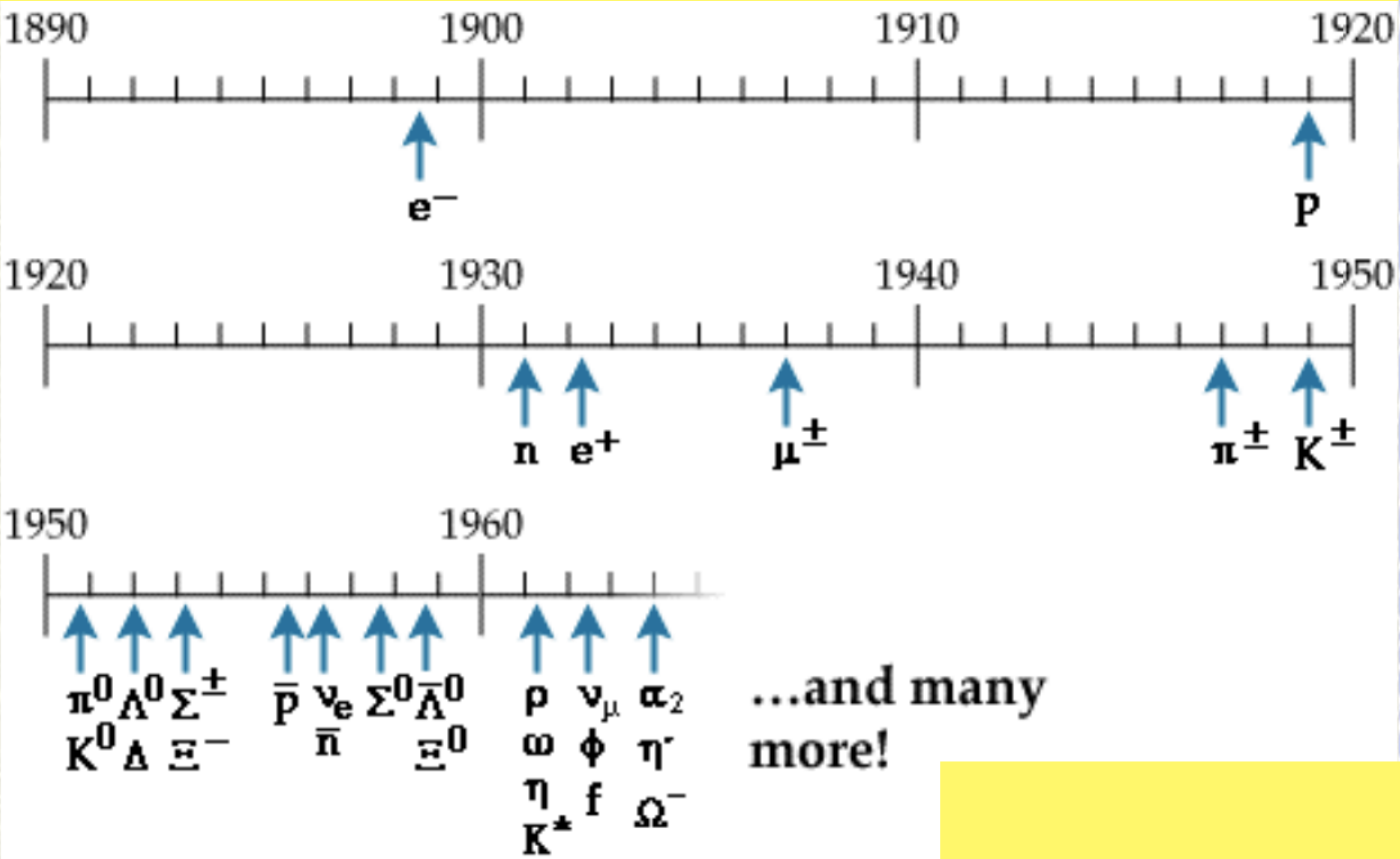
1912 - 2012: 100 anni di scoperte

La rivelazione della radiazione cosmica puo' essere considerata la scoperta del secolo e ha modificato la nostra visione del cosmo.

A ragione puo' essere considerata una pietra miliare degli inizi della fisica delle particelle

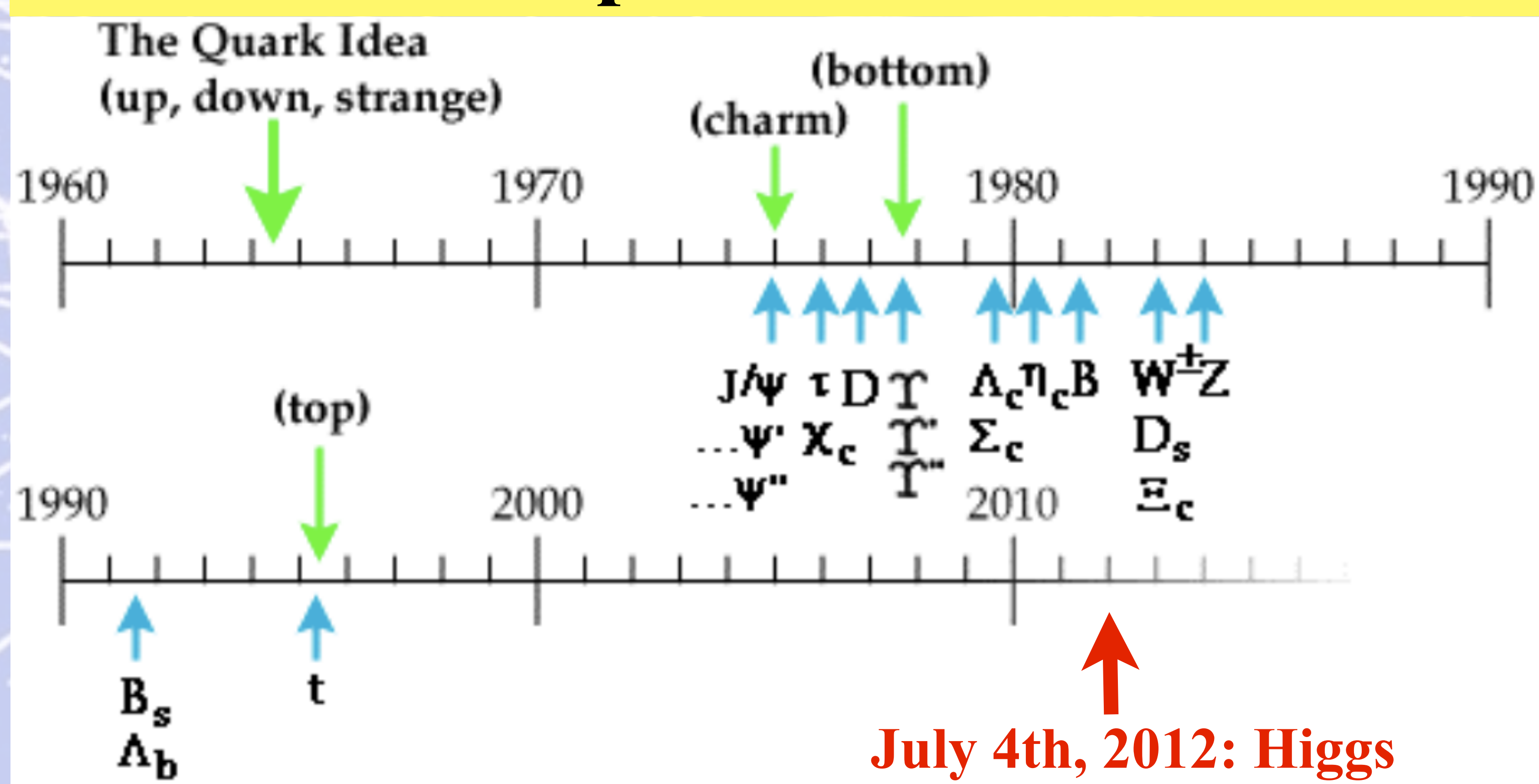
Prima dello sviluppo della fisica degli acecleratori, la ricerca sui raggi cosmici ha portato alla scoperta di molte importanti particelle elementari come ad esempio l'anti-particella dell'elettrone, il positrone, cosi' come il muone ed il pione.

Scoperte dal 1898 al 1964



Cronologia della scoperta delle particelle

Scoperte dal 1964



Cronologia delle Fisica delle Particelle

Gli inizi:
sinergia tra l'infinitamente piccolo e l'infinitamente grande

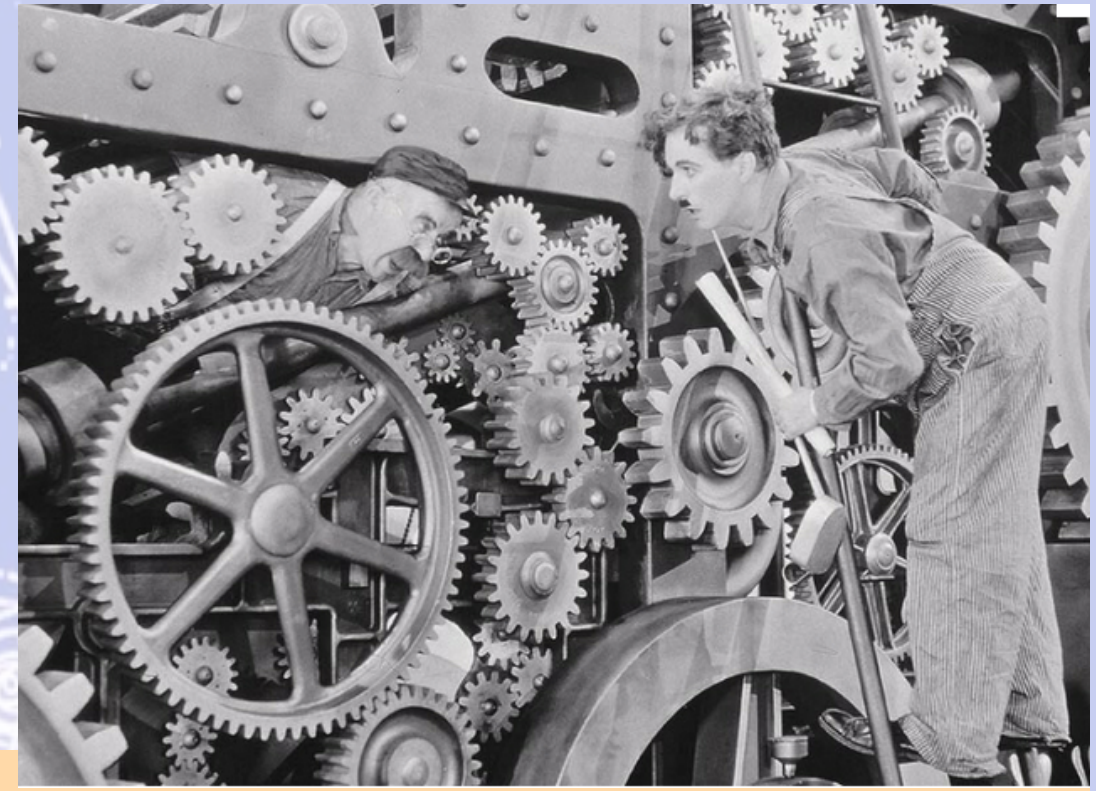
1895 Scoperta dei raggi X (W. Roentgen)
1896 Scoperta della radioattivita' (H. Becquerel)
1897 Scoperta dell'elettrone (J.J. Thomson)
1898 Isolamento del radio (M. Curie and P. Curie)
1905 Teoria della relativita' speciale (A. Einstein)
1909 La particella α e' un nucleo di elio (Rutherford and Royds)
1911 Scoperta del nucleo dell'atomo (E. Rutherford)
1912 Scoperta della radiazione cosmica (Victor Hess)
1913 Modello atomico planetario (N. Bohr)
1915 Teoria della relativita' generale (forma finale) (A. Einstein)
1919 Eddington osserva deviazione della luce in una eclisse totale del Sole
1926 Meccanica quantistica (E. Schrodinger)
1927 Equazione di Dirac e predizione delle anti particelle (P. Dirac)

Cronologia delle Fisica delle Particelle

Il periodo intermedio:
i tempi d'oro dell'infinitamente grande

1928 Teoria della radioattivita' α (Gamow, Gurney, Condon)
1930 Hubble scopre L'espansione dell'universo
1930 Ipotesi esistenza neutrino (W. Pauli)
1930 Invenzione del ciclotrone (E.O. Lawrence)
1932 Scoperta del neutrone (Chadwick)
1933 Scoperta del positrone nei raggi cosmici (Anderson)
1934 Teoria della radioattivita' β (E. Fermi)
1935 Ipotesi dei mesoni (Yukawa)
1937 Scoperta del muone nei raggi cosmici (Neddermeyer, Anderson)
1947 Scoperta del pione nei raggi cosmici(Powell)
1947 Scoperta kaone e "particelle strane"nei raggi cosmici (Rochester & Butler)
1950 Scoperta del barione "strano Λ (Hopper & Biswas)

Cronologia delle Fisica delle Particelle



Tempi Moderni:
l'era d'oro dell'infinitamente piccolo

1952 Altre particelle "strane" (Ξ, Σ) scoperte nei raggi cosmici.
1955 Scoperta dell'antiprotone al Bevatron (Chamberlain & Segre)
1956 Scoperta dell'antineutrone al Berkeley Bevatron
1956 Rivelazione sperimentale del neutrino (Reines, Cowan @ Los Alamos)
1974 Scoperta della risonanza J/ψ (quark Charm) (Richter & Ting)
1975 Scoperta del leptone τ (Perl SLAC-LBL)
1977 Scoperta del quark bottom (E288 Fermilab)
1983 Scoeprta dei bosoni W e Z (Rubbia & Van der Meer)
1995 Scoperta del quark top (D0 e CDF)
2000 Scoperta del neutrino τ (DONUT)
1995- Scoperta delle oscillazioni e della massa del neutrino (neutrino solare ed atmosferico) (Homestake, GALLEX, SAGE, Super-K, SNO, …)
2012 Scoperta del bosone di Higgs all' LHC (ATLAS, CMS)

Cronologia della Fisica delle Particelle

Per risolvere il "puzzle" delle particelle, i fisici richiedono delle energie sempre maggiori di quelle che la odierna tecnologia degli acceleratori e' in grado di offrire.
Ecco perche' alcuni di essi hanno deciso di

TORNARE ALLA RICERCA NEL COSMO !

Sin dalla meta' degli anni '80 fino ad ora, la fisica delle ASTRO-PARTICELLE e' stata un campo di attivita' sempre crescente.
Infatti, qualsiasi sia il metodo utilizzato per ricercare le particelle (dai raggi cosmici o utilizzando la tecnologia degli acceleratori) la maggior parte delle domande e' comune ad entrambi i campi.

Il Modello Standard della Fisica delle Particelle

100 anni per svilupparlo!

Verificato con incredibile precisione!

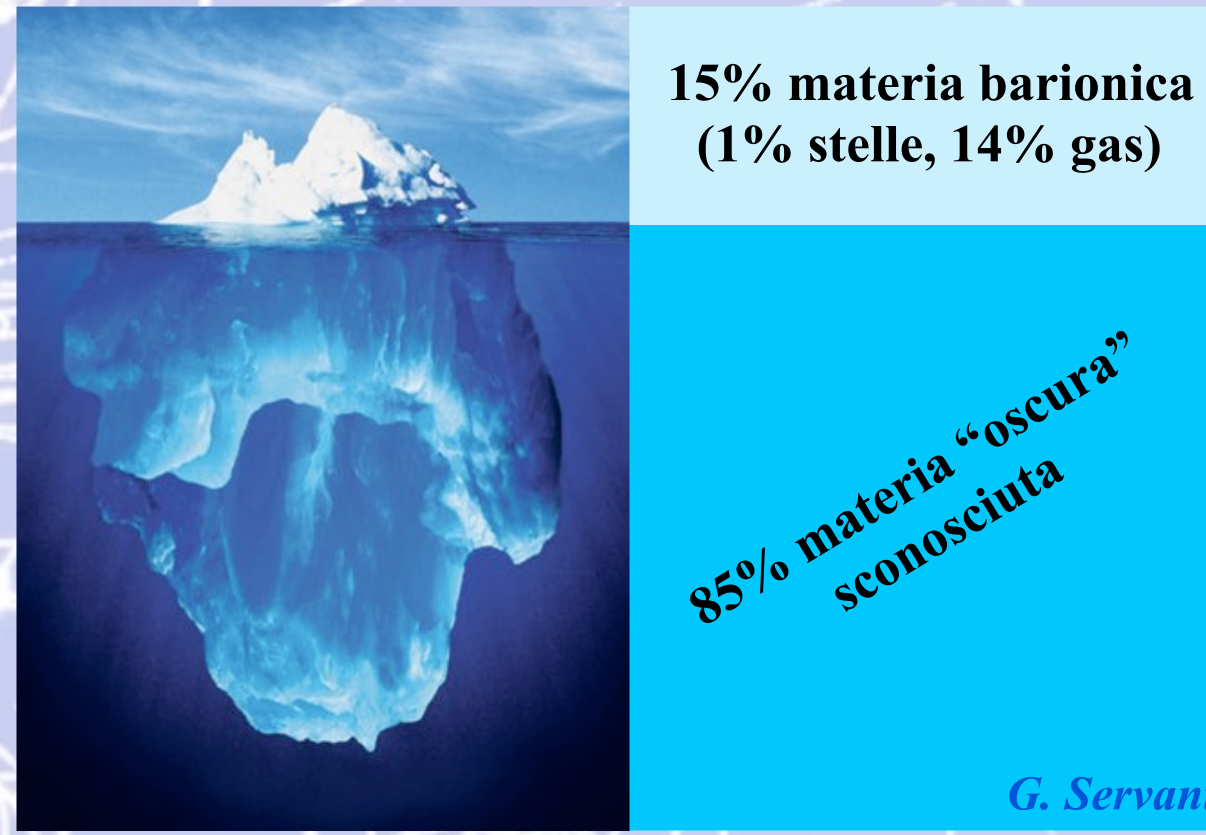
Tiene conto di tutti i dati raccolti della fisica delle particelle!

Il bosone di Higgs era il solo "pezzo del puzzle" rimasto inosservato e rappresenta un portale verso settori nascosti di nuova fisica

Ci sono due osservazioni non ancora spiegate dal Modello Standard che potrebbero essere correlate con nuova fisica alla scala elettrodebole

Materia Oscura nell’Universo

Un tipo di materia invisibile e trasparente (non interagisce con i fotoni) la cui presenza e’ dedotta attraverso i suoi effetti gravitazionali.

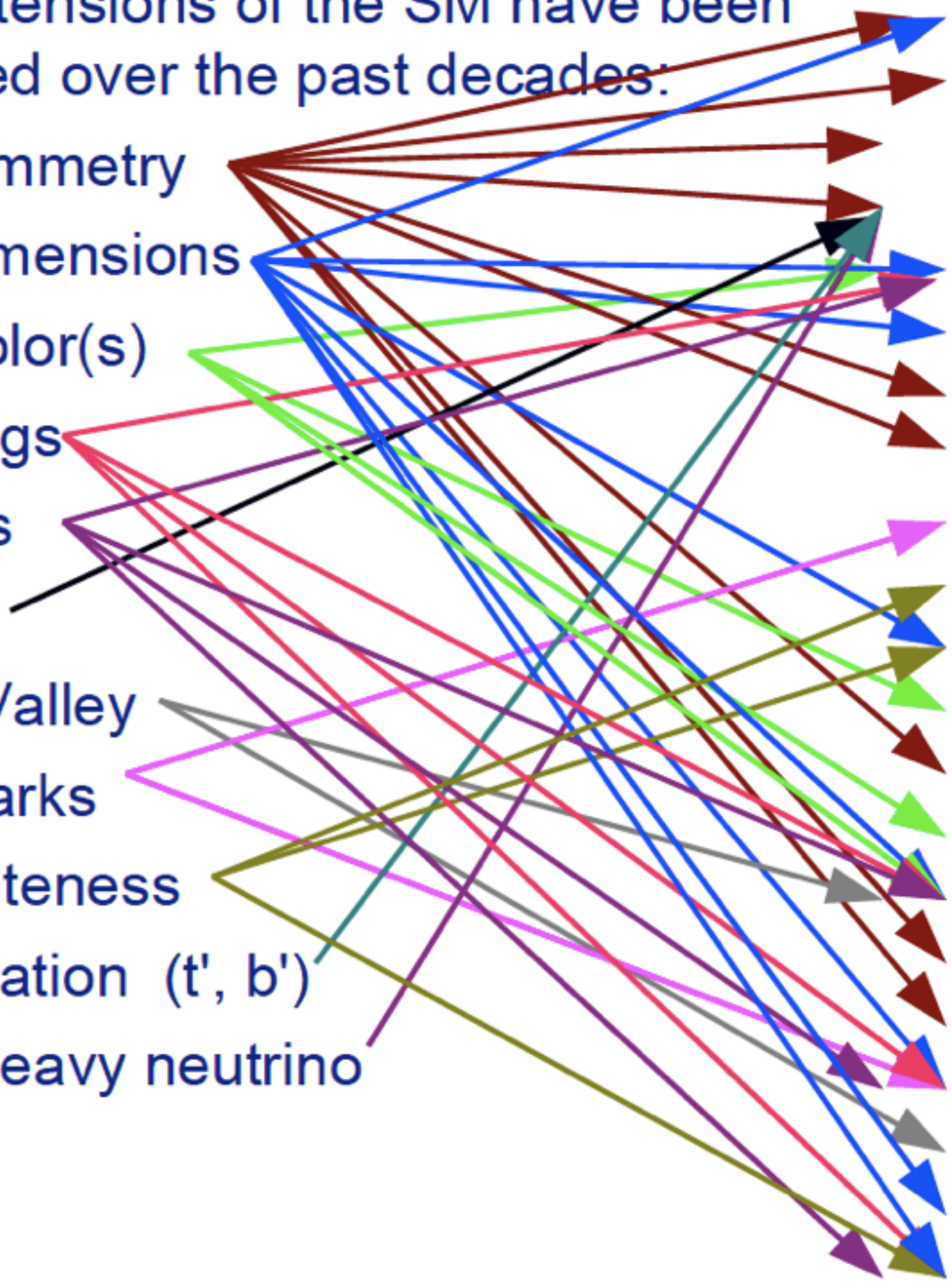


(Quasi) assenza di antimateria nell’ Universo

Asimmetria barionica: $\frac{n_B - \bar{n}_B}{n_B + \bar{n}_B} \sim 10^{-10}$

Dall' LHC non ci sono ancora segni di nuova fisica

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...



- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

(for illustration only)

G. Servant

Candidati della Materia Oscura: due principali possibilita'

molto leggera & accoppiamento solo gravitazionale → stabile su scale cosmologiche

Long-lived
(stabile su scale cosmologiche)

$\tau_{DM} > \tau_{universe} \sim 10^{18}$ s

DM = Dark Matter

OR

interazione misurabile (ma non per via forte) con lo SM → simmetria necessaria per garantire a stabilita'

stabile rispetto ad una simmetria

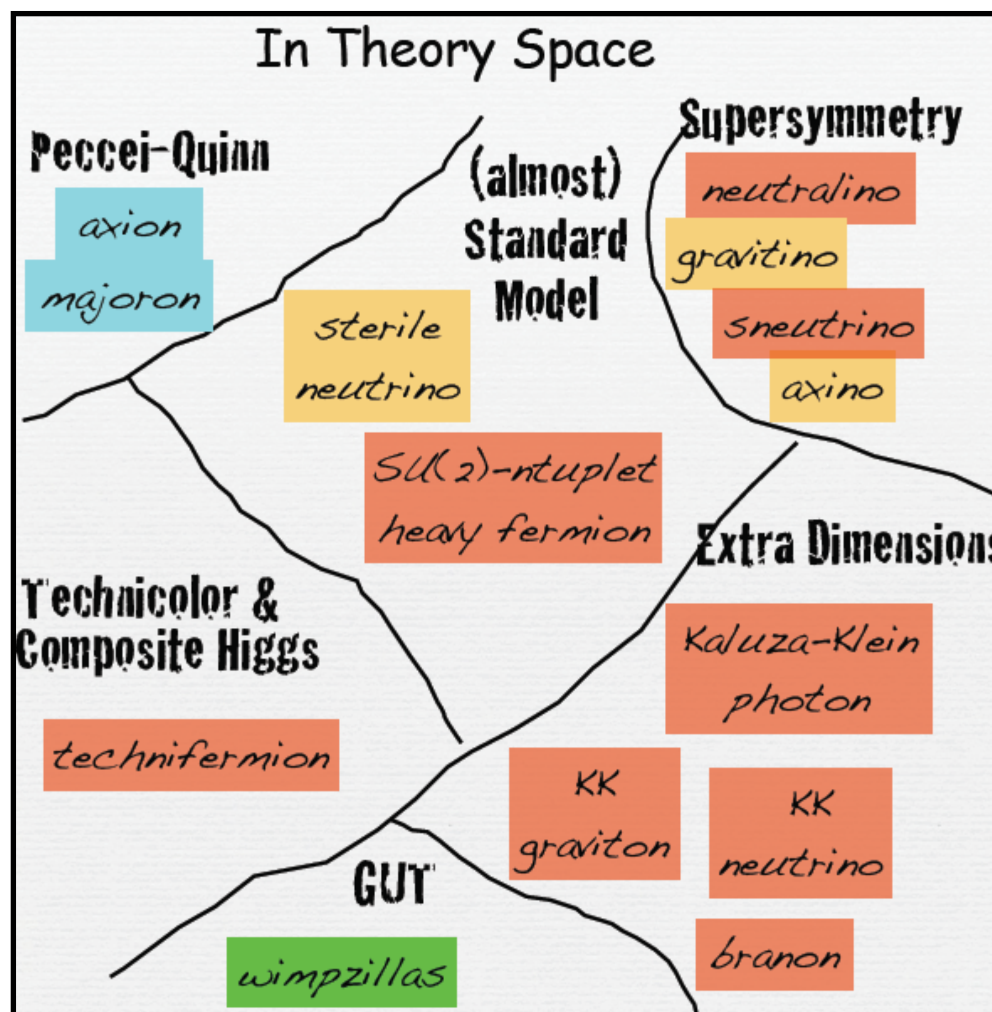
WIMP

WIMP = Weak Interactive Massive Particle

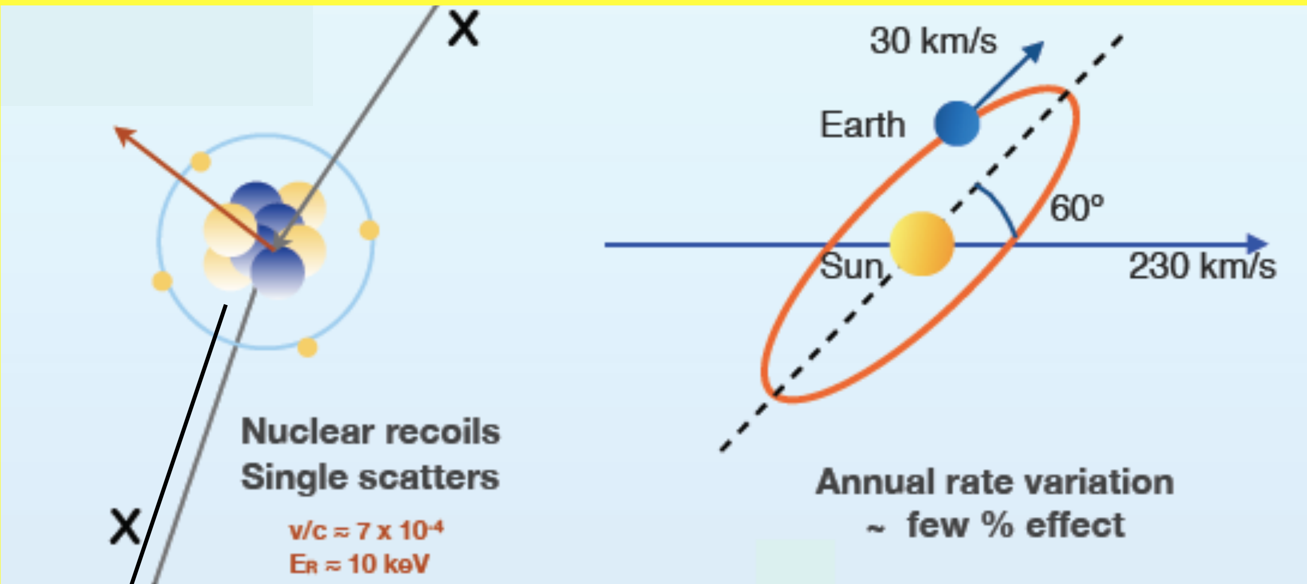
La restante abbondanza di un tipo di particella stabile segue dal generico meccanismo di "freeze-out" termico dell'espansione dell'universo.

Thermal relic: $\Omega_{DM} \propto 1/\sigma_{annih}$

$\sigma_{annih} \approx$ 1pb conduce alla corretta abbondanza di DM



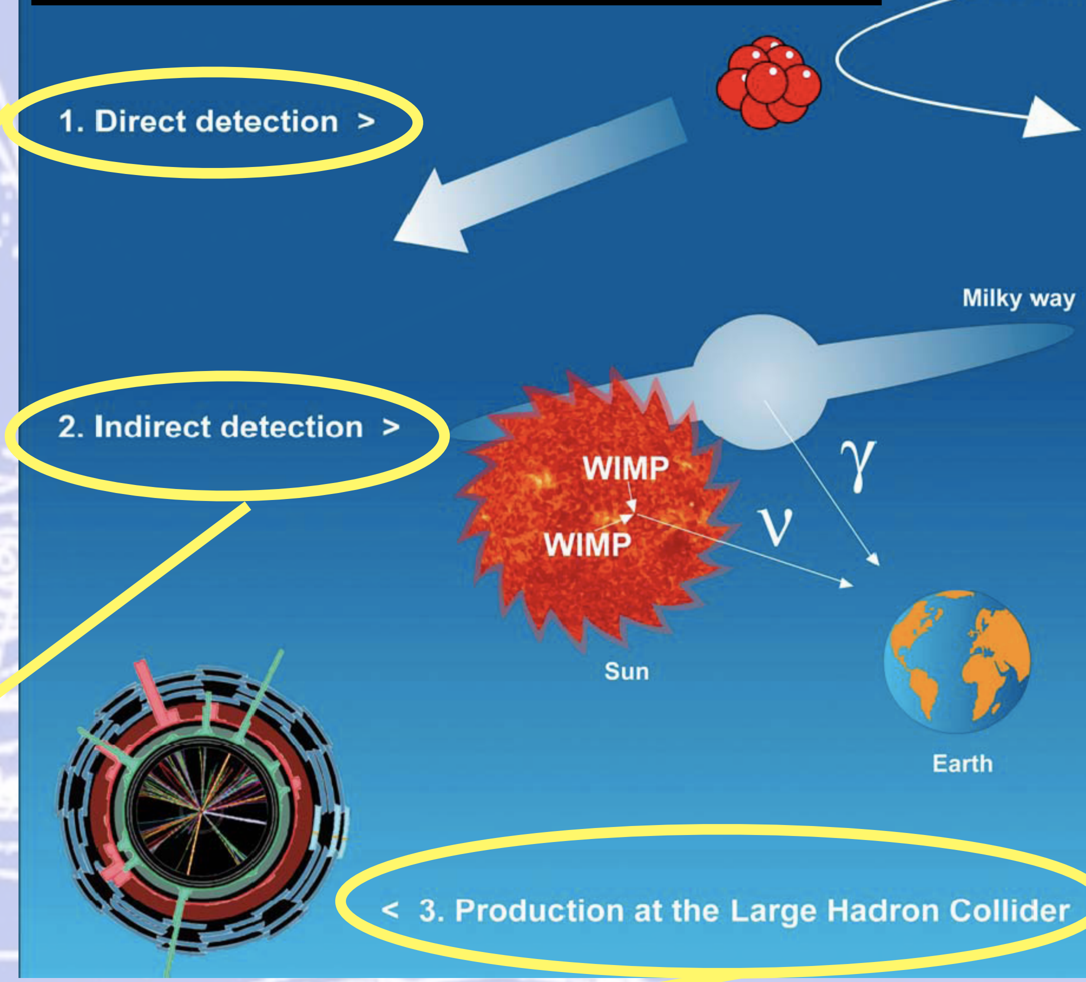
Candidati della Materia Oscura con $\Omega_{DM} \sim 1$



WIMP flux on Earth: ~ 10^5 $cm^{-2}s^{-1}$ (for a 100 GeV WIMP)

Segnale di "Elastic Scattering" in esperimenti sotterranei

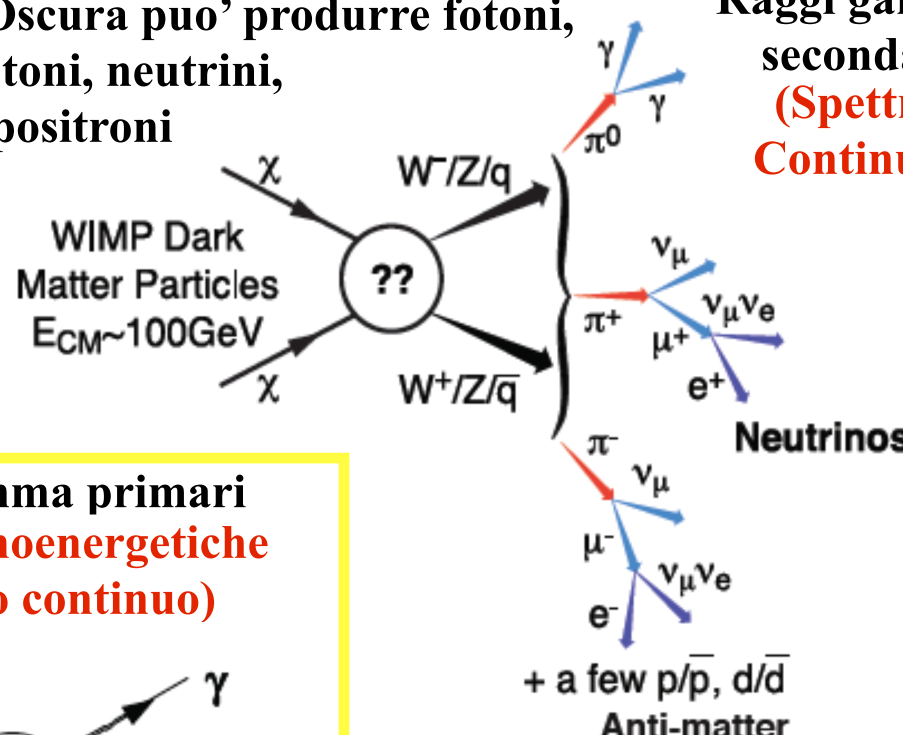
Strategie ricerca Materia Oscura



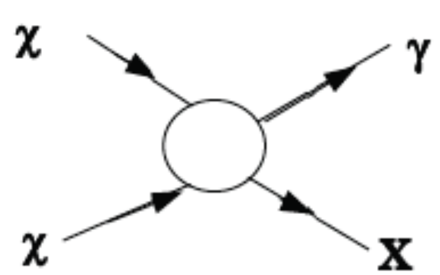
Segnale di annichilazione nello spazio

La Materia Oscura puo' produrre fotoni, elettroni, protoni, neutrini, antiprotoni, positroni

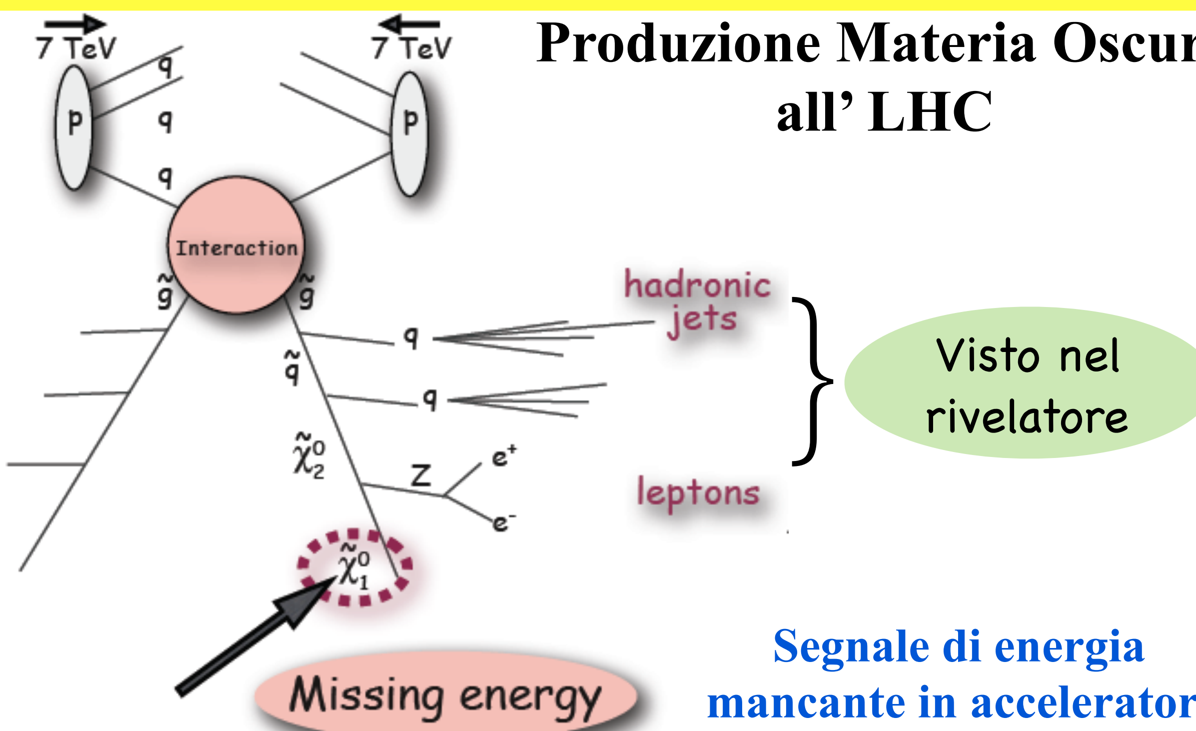
Raggi gamma secondari (Spettro Continuo)



Raggi gamma primari (Linee monoenergetiche o spettro continuo)



Produzione Materia Oscura all' LHC



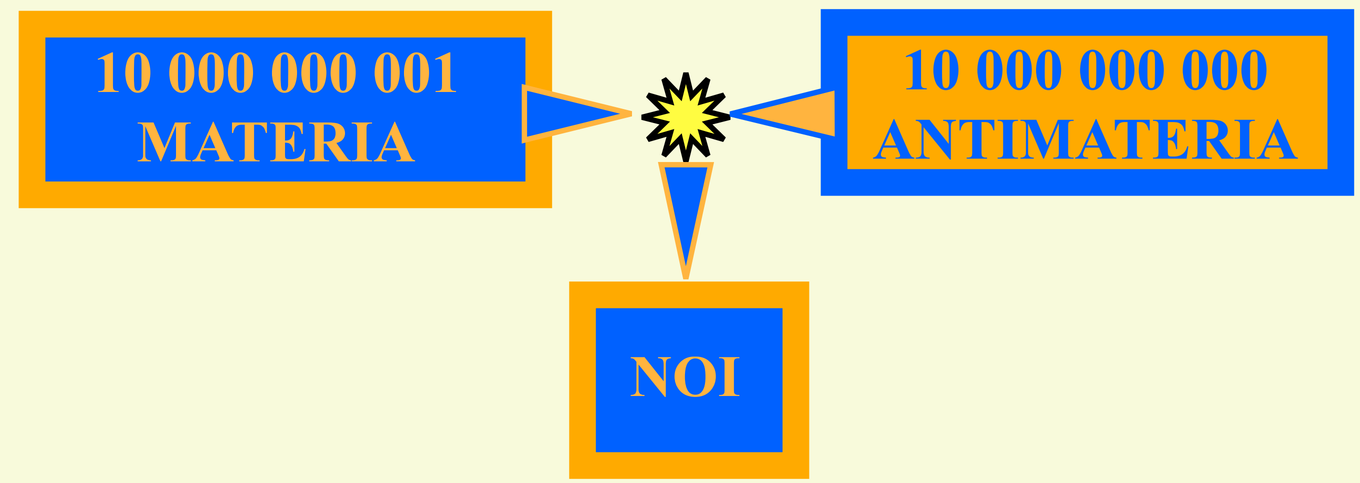
Segnale di energia mancante in acceleratori di alta energia

Antimateria: problemi e domande

La Teoria del Big Bang richiede una uguale abbondanza di materia e antimateria.

Dopo l'inizio dell' "era" delle particelle, non si e' trovato alcun processo che possa cambiare il numero netto di particelle dell'universo.

A partire da un millisecondo dopo il Big Bang, il bilancio tra materia ed antimateria e' stato fissato per sempre.



Esiste una qualche ASIMMETRIA nel modo in cui la natura tratta materia e antimateria?

Una linea di investigazione molto promettente e' quella delle CP violazioni della simmetria CP nei decadimenti di particelle via interazione debole.

La principale evidenza sperimentale proviene dal decadimento del kaone neutro, che mostra una piccola violazione della simmetria CP. Nel decadimanto dei kaoni in elettroni, abbiamo una netta distinzione tra materia e antimateria, e cio' potrebbe essere almeno una delle spiegazioni della predominanza di materia rispetto all'antimateria nell'universo.

Una prima evidenza (3.5σ) si e' avuta a LHCb con 0.8% di differenza nel tasso di decadimento del mesone D e della sua antiparticella (2011).

Questo potrebbe essere un altro contributo alla soluzione del problema dell'antimateria.

Antimateria: problemi e domande

La presenza di antimateria entro il nostro gruppo di galassie e' esclusa: il segnale di annichilazione e' troppo piccolo.

...ma se una volta e' esistita, dov'e' ora ?

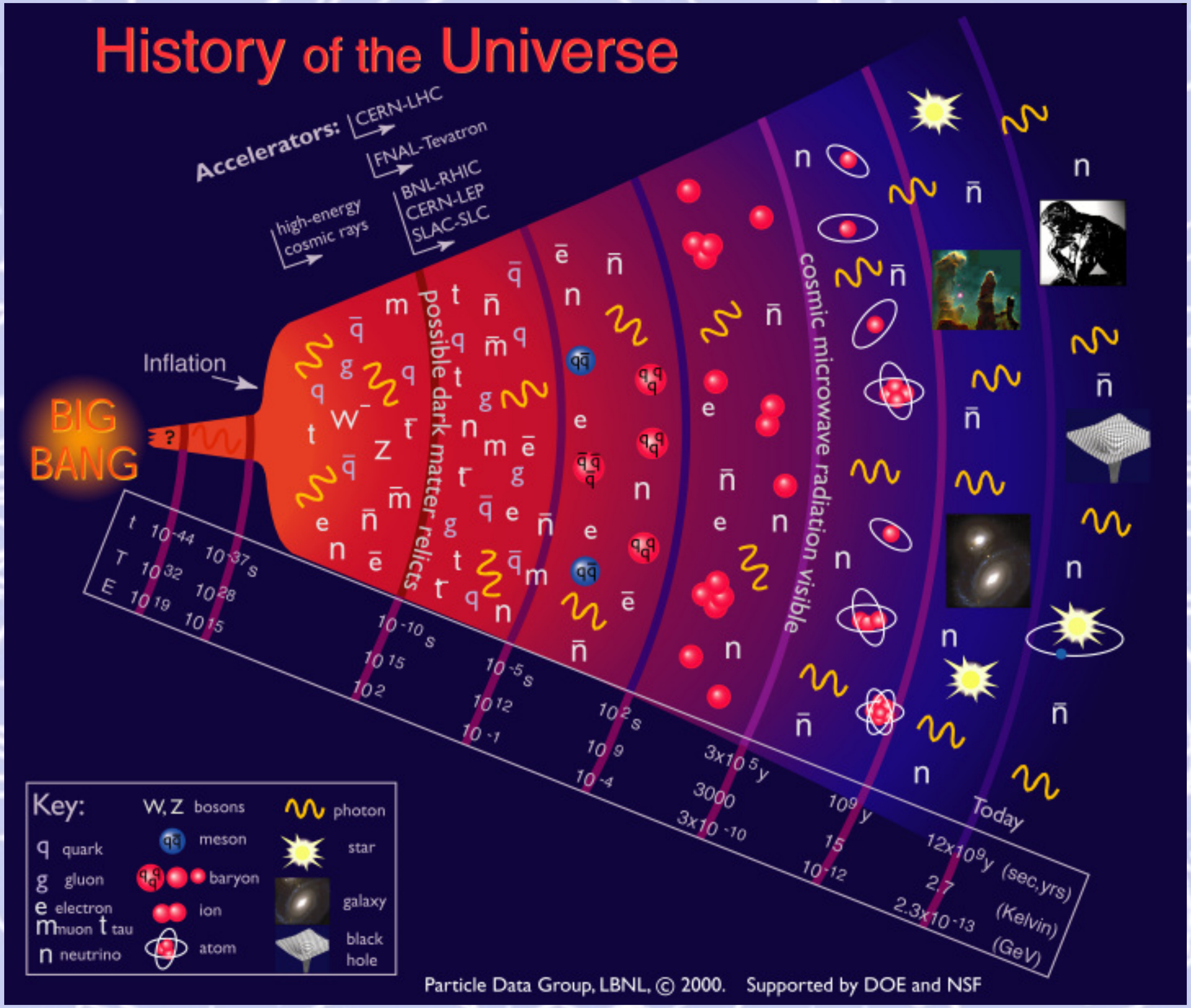
Lontano da noi ?

Esiste un qualche resto di antimateria nell'Universo vicino?

Singolo nucleo di anti-He nei raggi cosmici:
Agglomerati di Antimateria

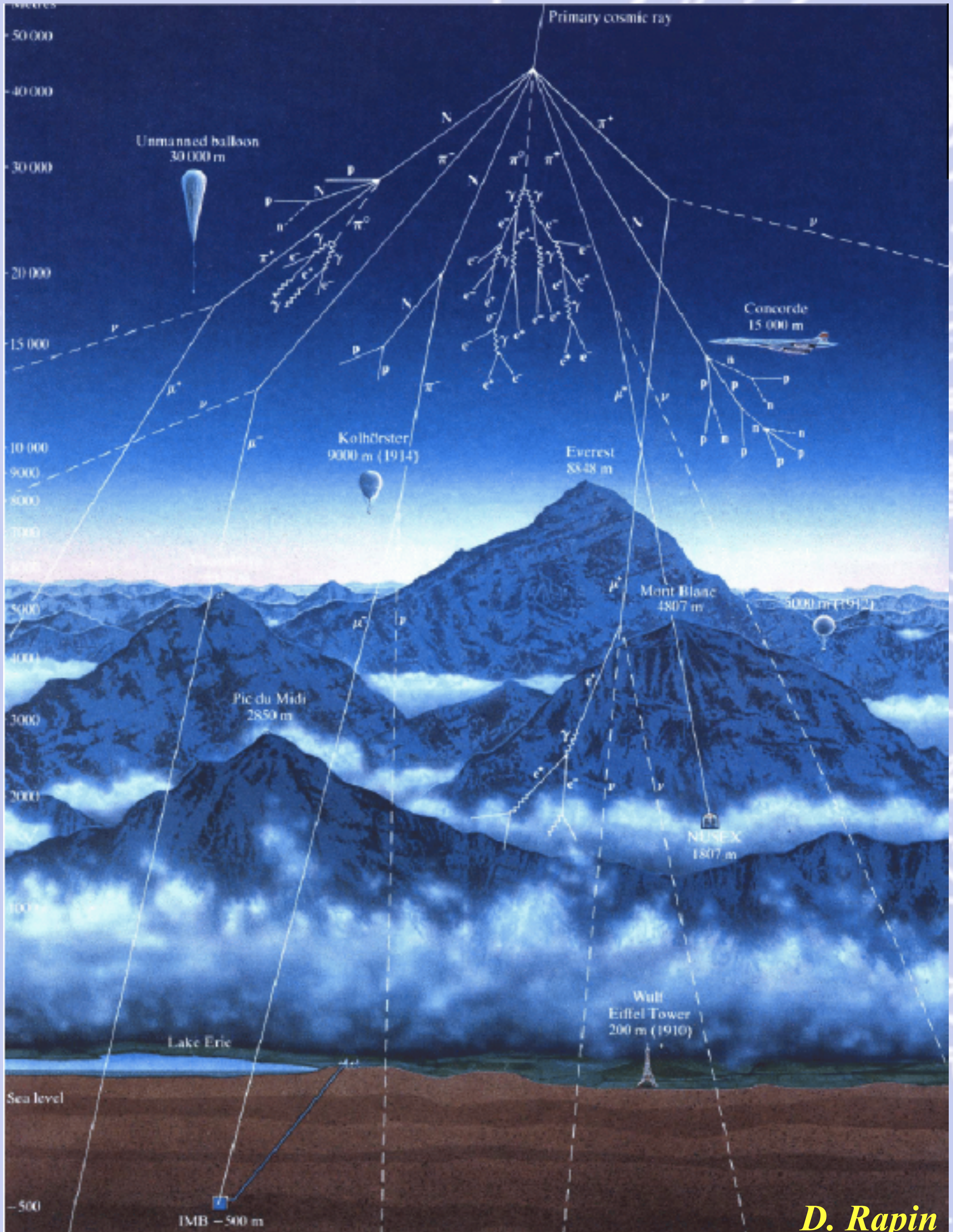
Singolo nucleo di anti-C nei raggi cosmici:
Stelle di Antimateria

NON conosciamo ancora la fisica dei primi istanti dopo il BigBang !



…. Materia Oscura e Antimateria sono solo due esempi tra i tanti segreti dell’ Universo!

Perche' investigare nello spazio?



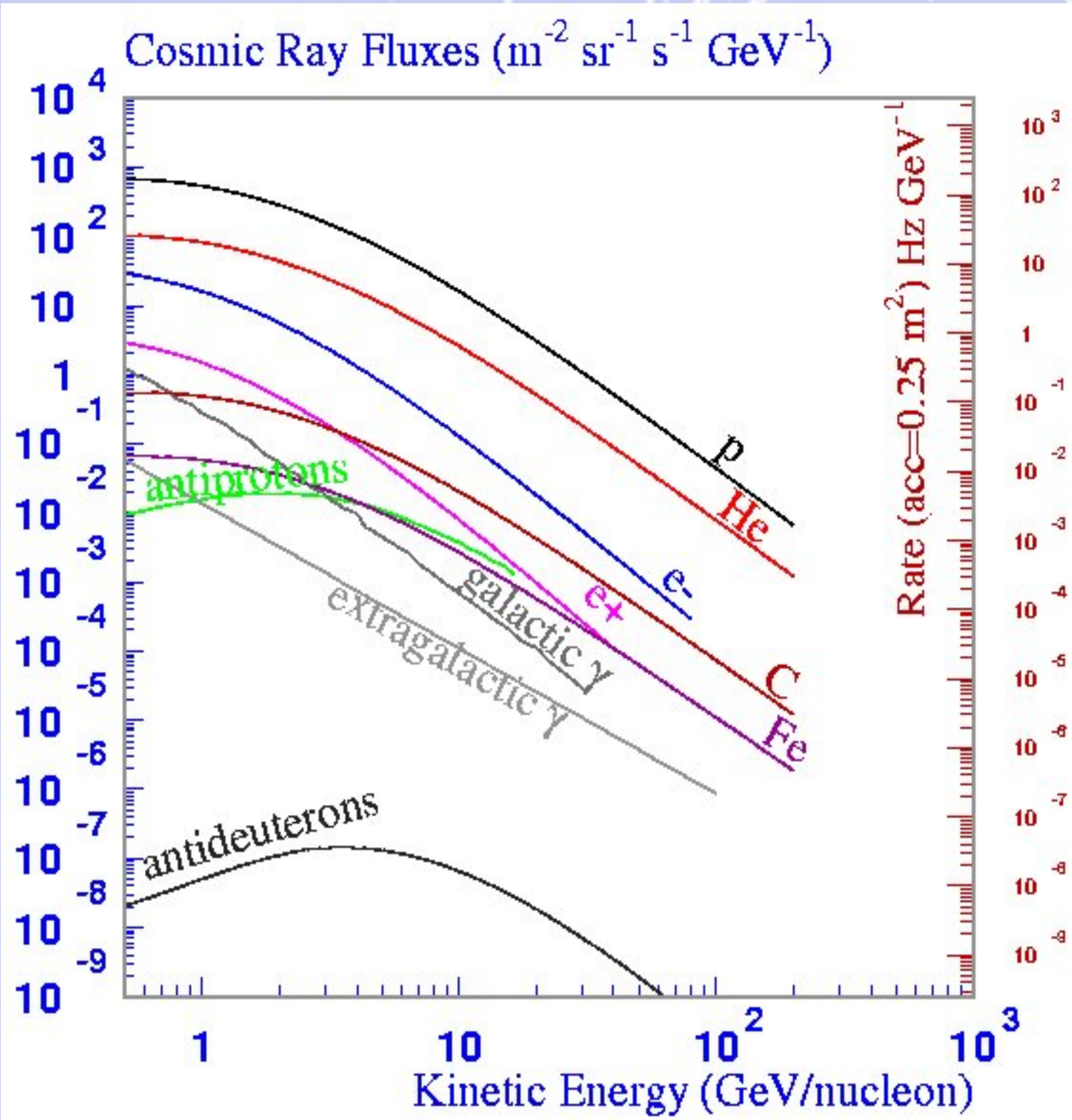
L'atmosfera non e' transparente alle particelle cariche o ai raggi X e gamma: le interazioni degradano l'informazione della particella iniziale.

Il suo spessore in termini di massa (1kg/cm²) e' equivalente ad uno schermo di 4 m di cemento.

Palloni aerostatici a 35 km (5 g/cm²) ma il tempo di esposizione e' limitato a ~20 giorni.

I rivelatori su satellite hanno un tempo di esposizione piu' lungo dell'ordine di qualche anno (3→15).

Qual e' la composizione dei Raggi Cosmici primari?



- p: componente dominante
- He: 5% del flusso p @ 10GeV
- D, Li, Be, B e C
- Anti-protoni: ~ 10^{-4} del flusso p

Protoni: un modo per misurare l'attivita' solare

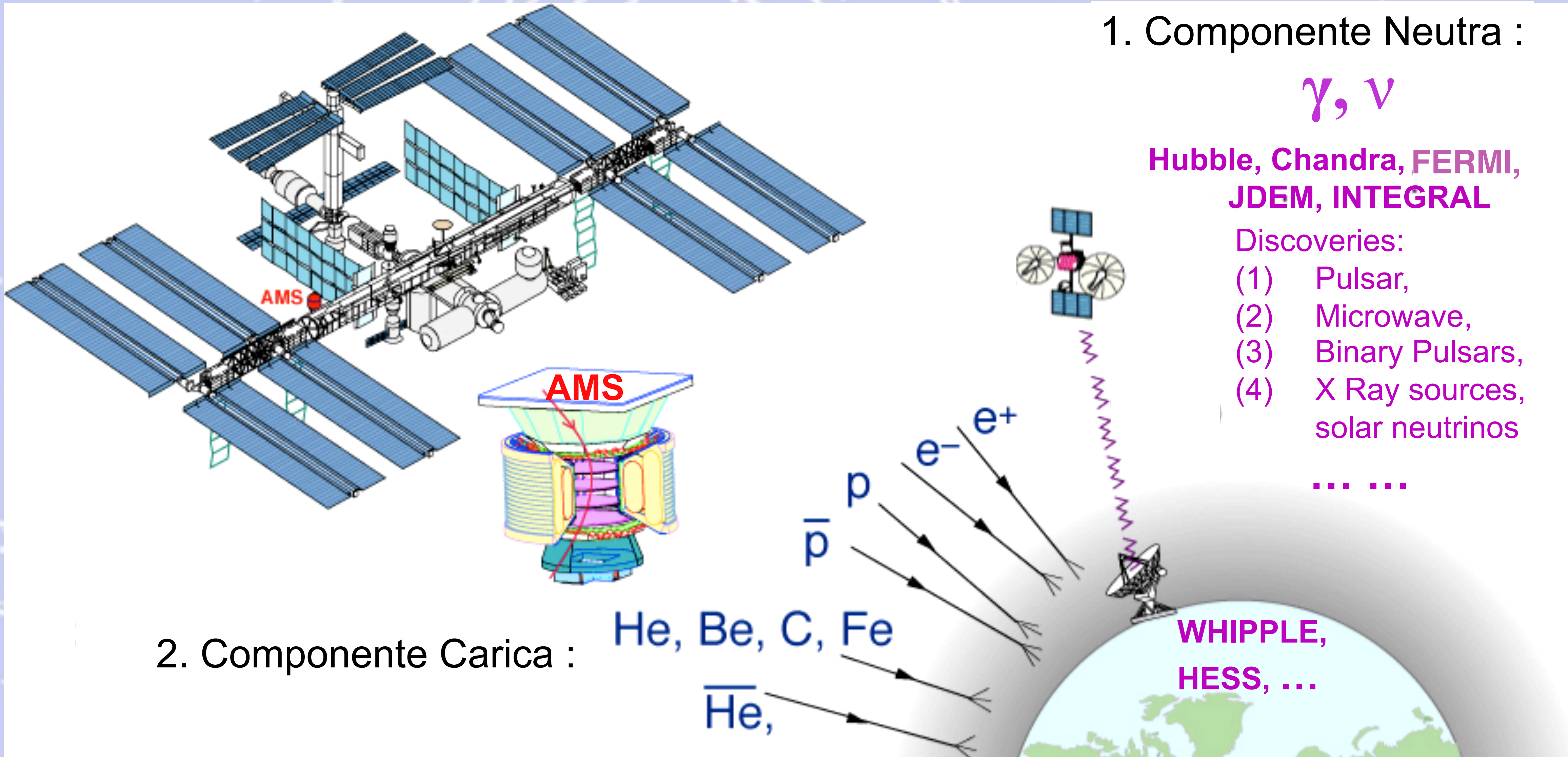
Isotopi: informazioni sulla propagazione dei Raggi Cosmici nella Galassia.

^{10}Be/^{9}Be ratio (^{10}Be, $\tau_{½}$=1.6x10^6yrs):

- Tempo di confinamento dei Raggi Cosmici nella Galassia.
- Densita' media del materiale interstellare attraversato.

L’ esperimento AMS-02 sulla ISS

AMS-02: un esperimento “multipurpose” di fisica delle particelle operante nello spazio



Le principali ricerche di AMS-02 sono:

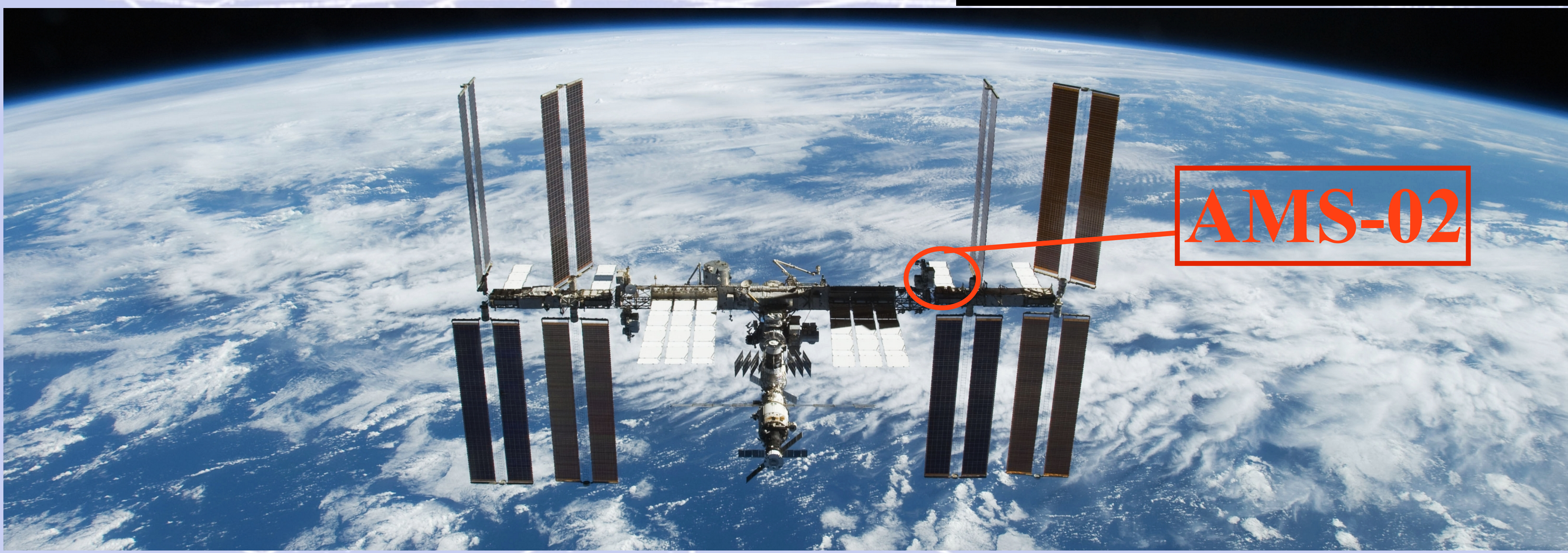
- **Antimateria;**
- **Studi di precisione dei Raggi Cosmici;**
- **Materia Oscura;**
- **Raggi γ di alta energia (diffuse, sources);**
- **Nuova fisica?…...strangelets???**

Lancio: 16 Maggio 2011, 08:56 AM

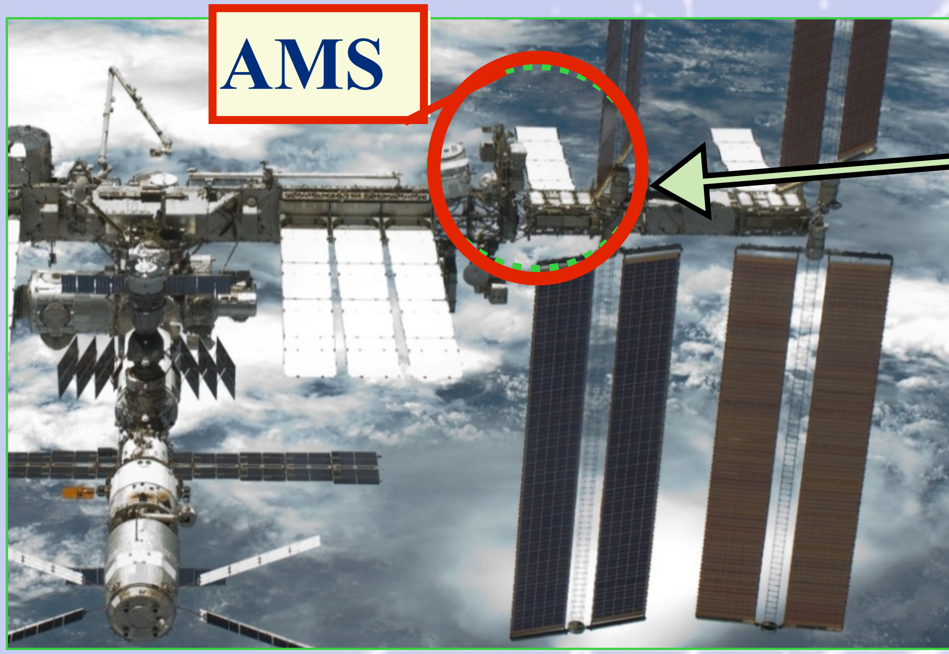
Installazione: 19 Maggio2011, 05:15 AM

Peso Totale: 2008 t
Peso AMS-02: 7.5 t

Presa dati iniziata alle 9:35 AM

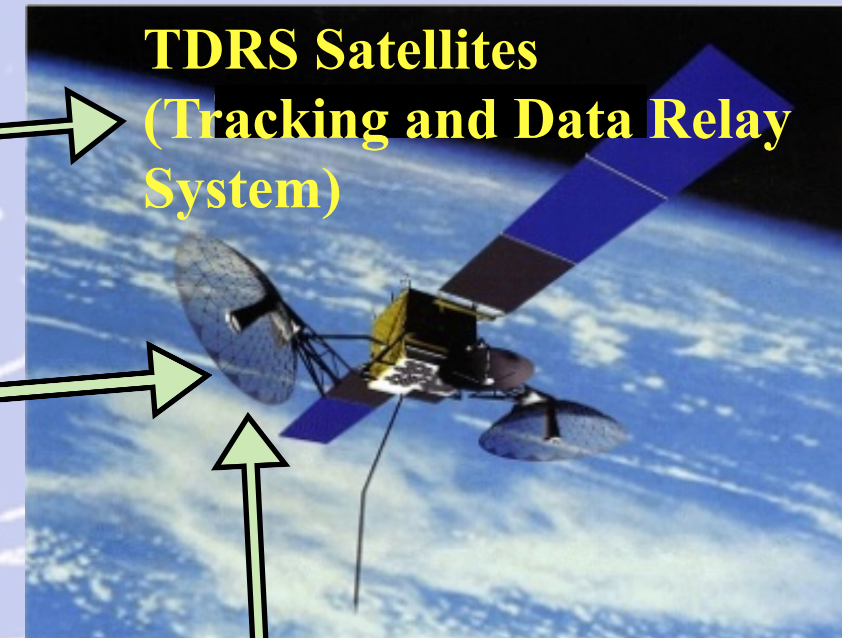

AMS-02

Come opera AMS-02 in volo e a terra



AMS

Astronauta usa il "laptop" di AMS presente sulla ISS



TDRS Satellites (Tracking and Data Relay System)

Ku-Band
High Rate (down):
Events <10Mbit/s>

Flight Operations

Ground Operations

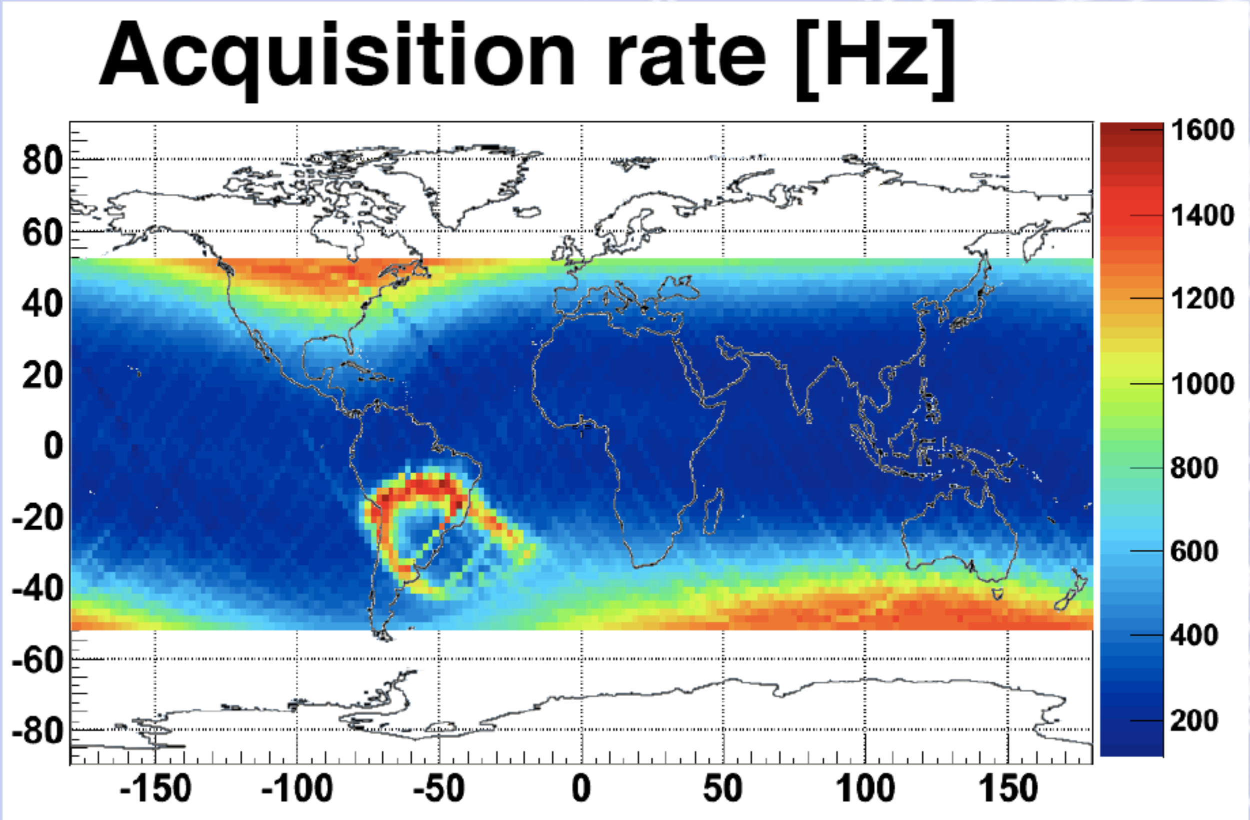
S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s

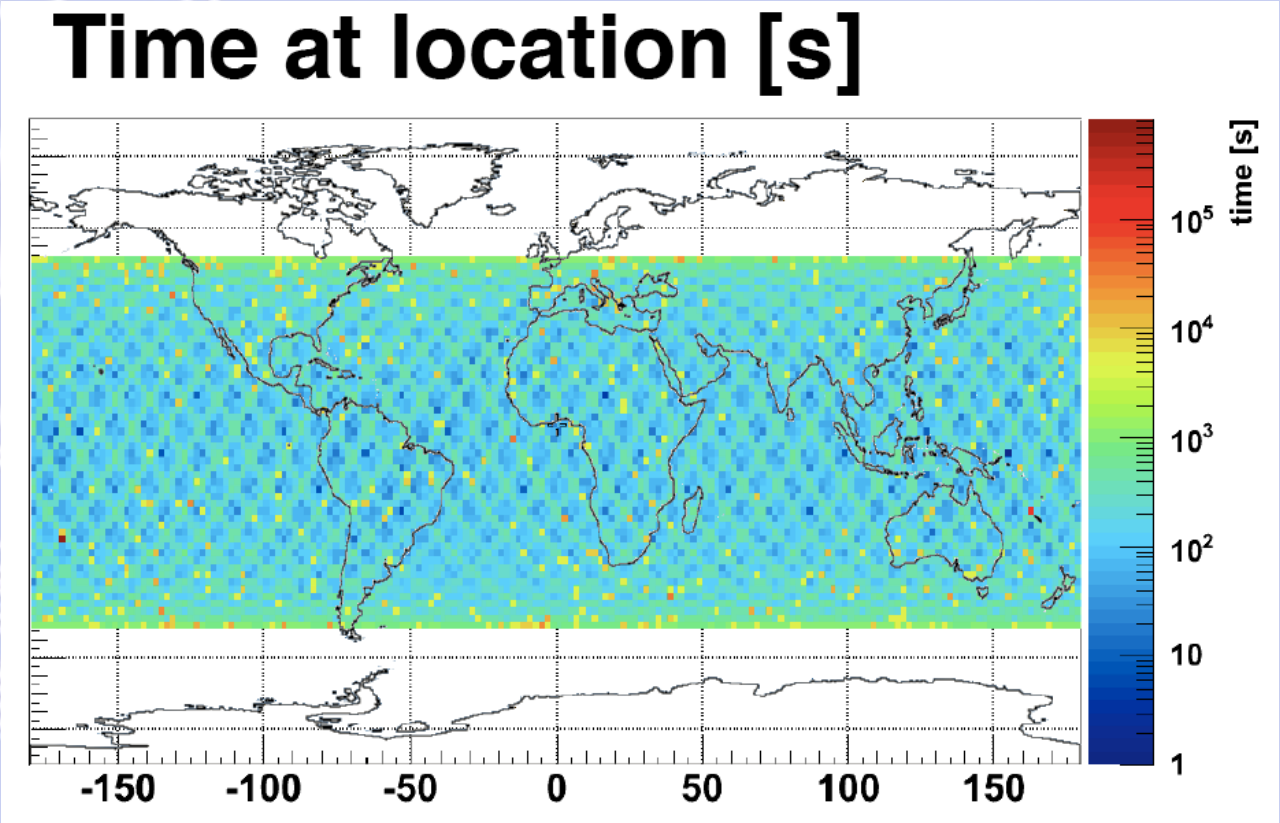
AMS Payload Operation Control and Science Operation Centers (POCC,SOC) at CERN

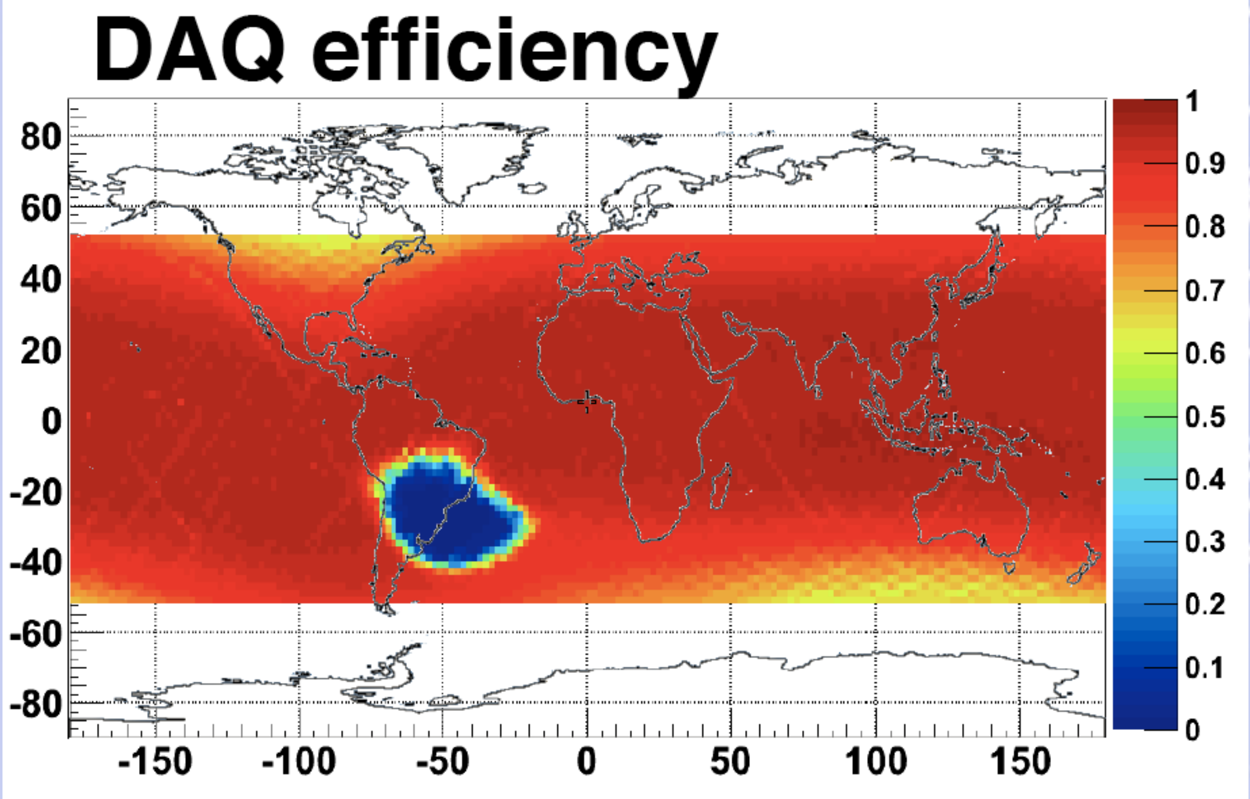
AMS Computers MSCF, Alabama

White Sands Ground terminal, NewMexico

Parametri orbitali del DAQ di AMS-02



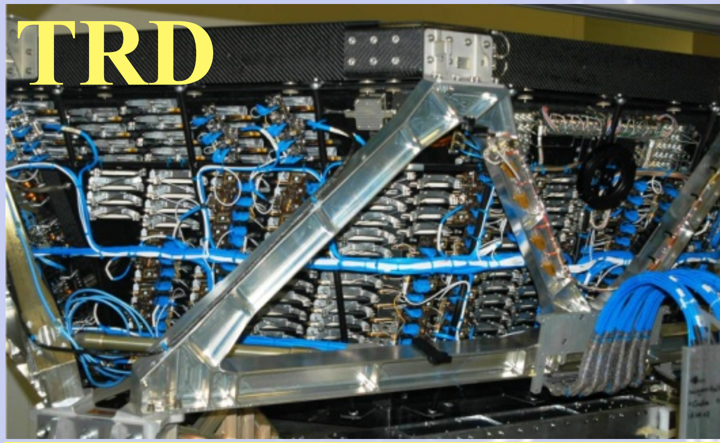




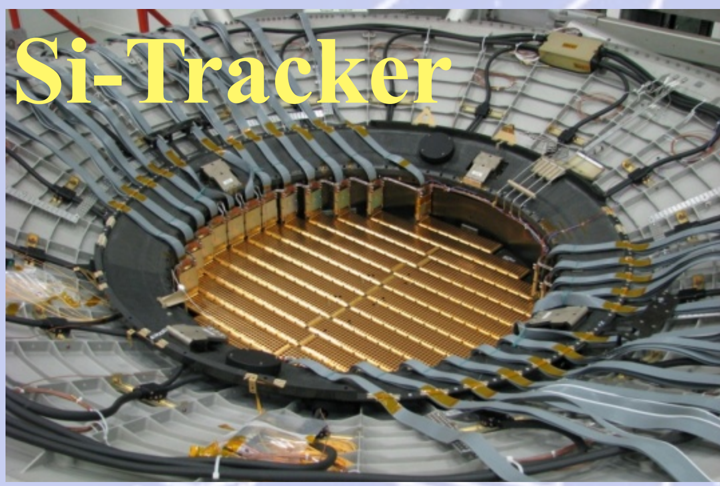
“Particles rate” varia da 200 to 2000 Hz per orbita

In media:
DAQ efficiency 85%
DAQ rate ~700Hz

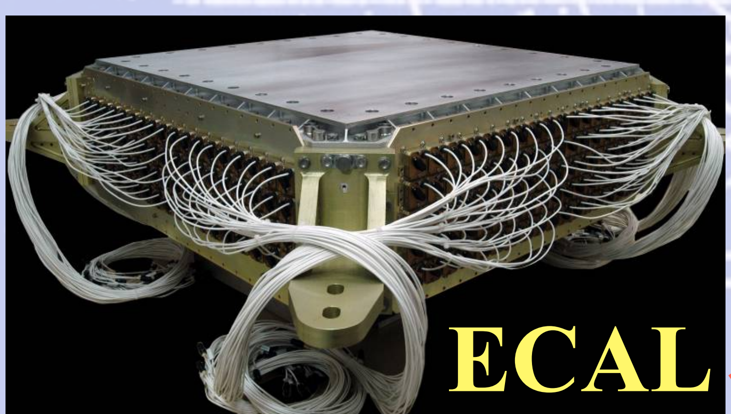
AMS-02: uno spettrometro di precisione per energie GeV/TeV



Identify e^+, e^-, Z

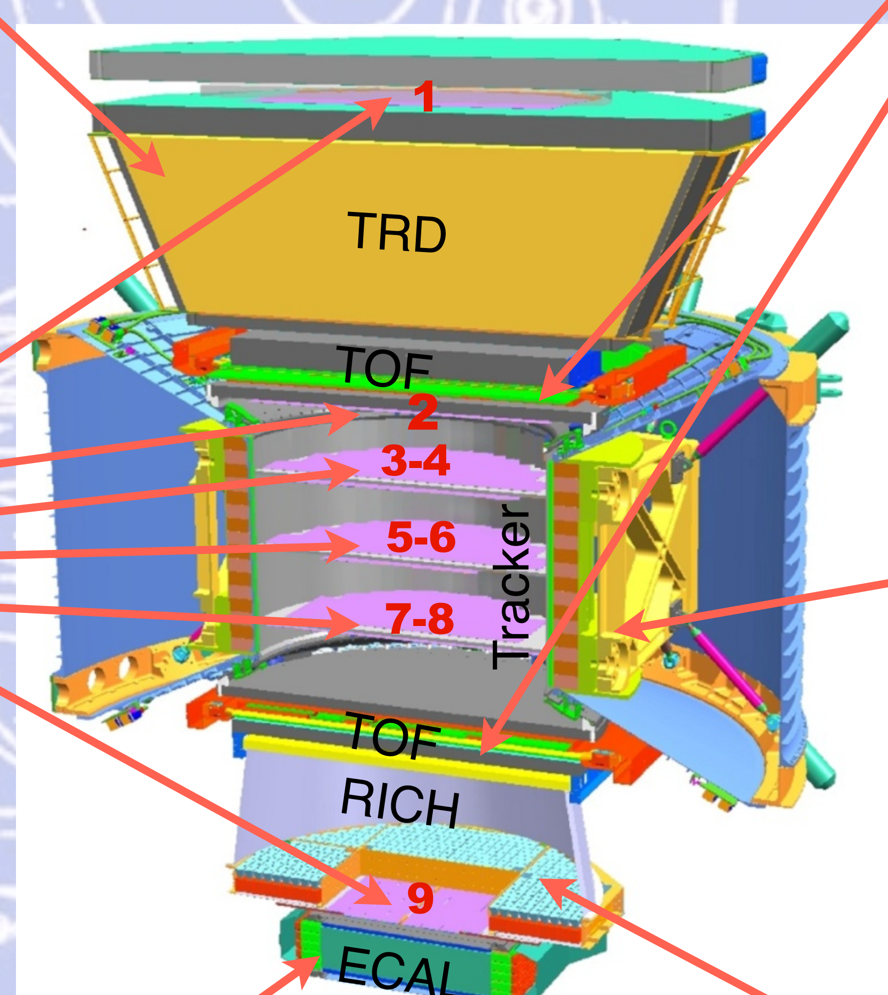


Identify Z, Measure P



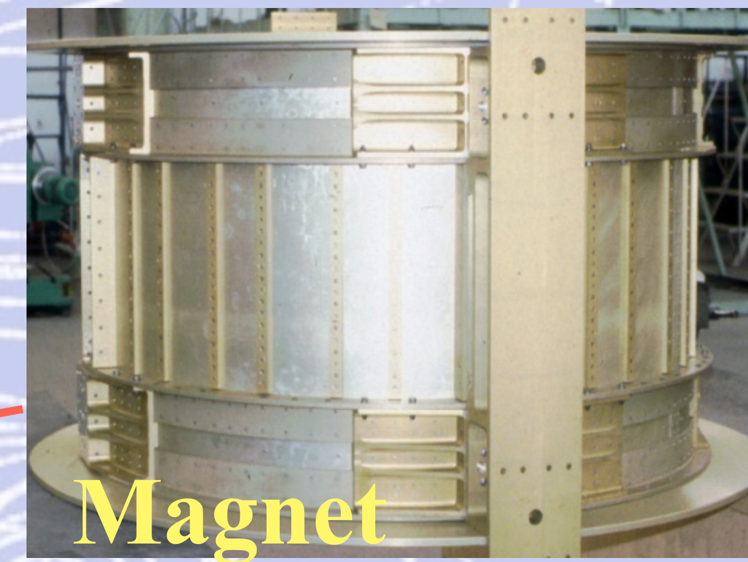
Measure E of e^+, e^-, γ

Le particelle ed i nuclei sono definiti dalla loro carica (Z) e dall'energia (E~P)



Z, P sono misurati independentemente dal Tracker, RICH, TOF e ECAL

Identify Z, Measure E



Identify ± Z

Identify Z, Measure E

Potenziale di fisica di AMS-02

Ricerca dell'antimateria primordiale:
- anti-nuclei: $\overline{He}$, … ;

Ricerca della Materia Oscura:
- e^+, $e^\pm$, $\bar{p}$, γ, … ;.
- osservazione simultanea di diversi canali di segnale ;

Ricerca di nuove forme di materia :
- strangelets, … ;

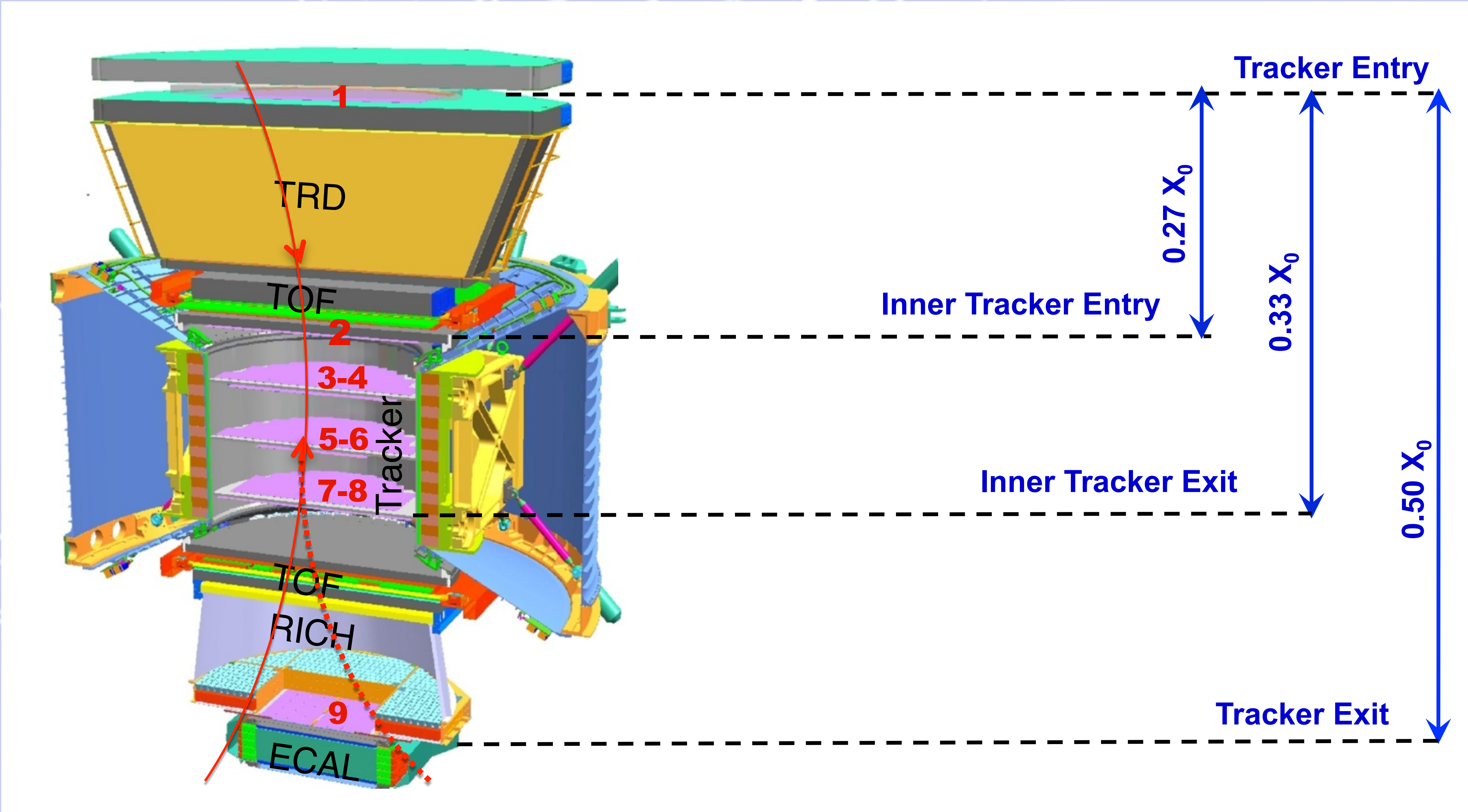
Misura degli spettri dei CR - "fine tuning" del modello di propagazione:
- D, He, Li, Be, B, C …Fe;

Studi di sorgenti locali (astrofisica dei raggi γ):
- SuperNovae Remnants, Pulsars, Primordial Black Holes, …….

Studio degli effetti della modulazione solare sugli spettri dei CR lungo tutto il ciclo solare (11 anni) ;

……….

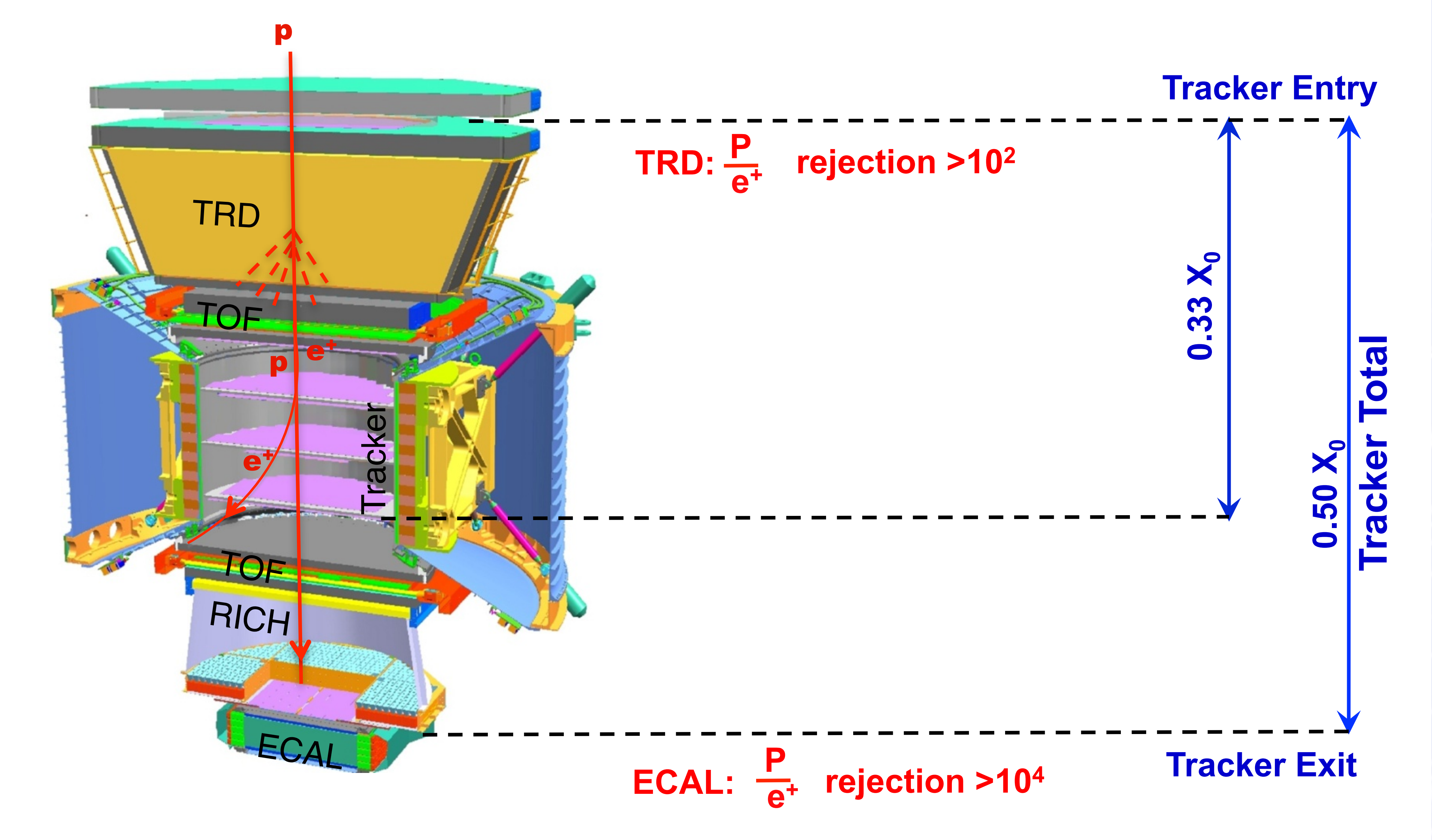
Sensitivita' della ricerca dell'Antimateria: $He/\overline{He} > 10^{10}$



a) Minimo materiale nel rivelatore:
quindi il rivelatore NON diventa una sorgente di " large angle scattering";

b) Misure ripetute dell'impulso:
per assicurare che le particelle con "large angle scattering" non siano confuse con il segnale.

Sensitivita’ della ricerca dell’origine della materia Oscura: $p/e^+ > 10^6$

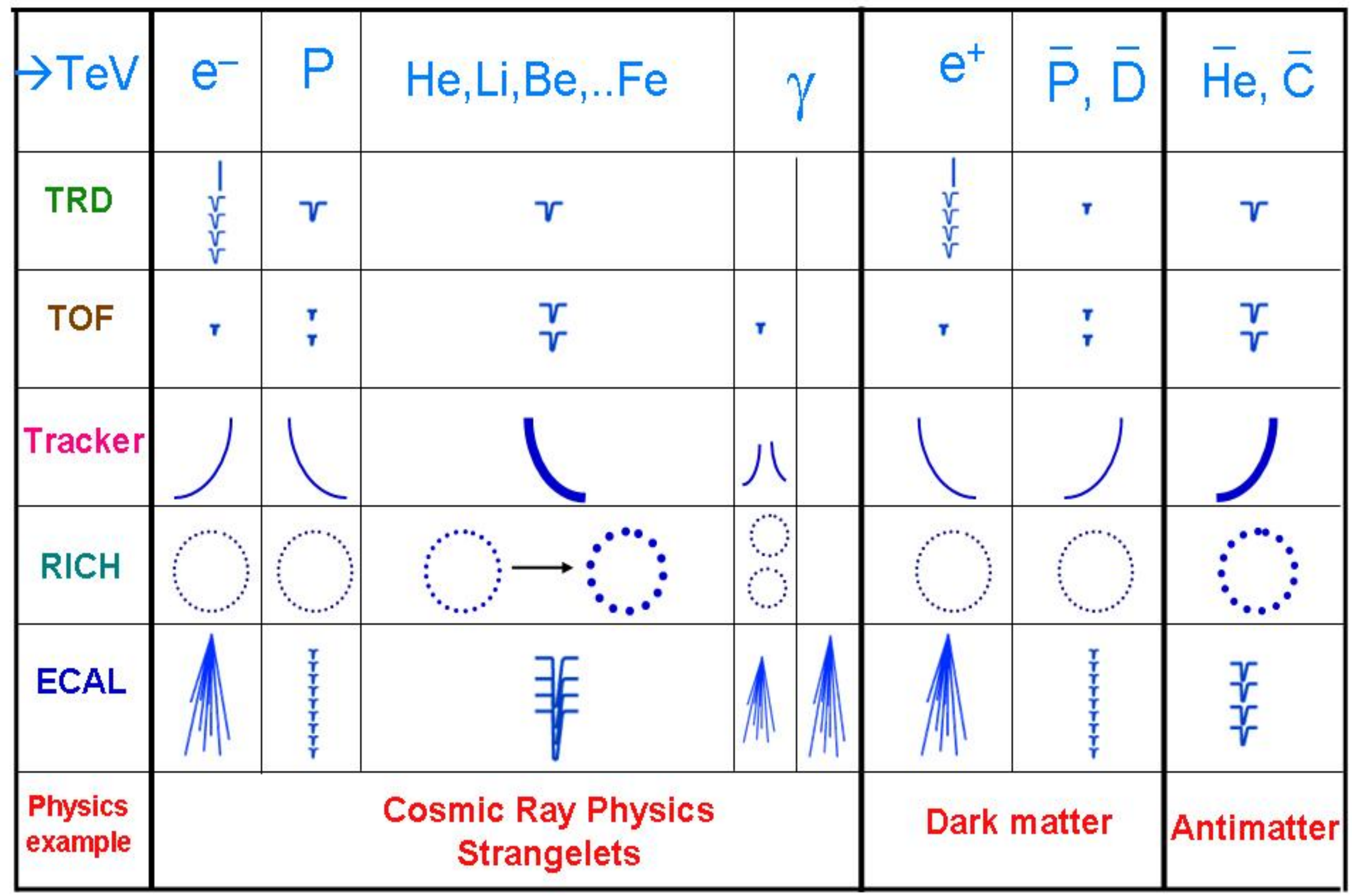


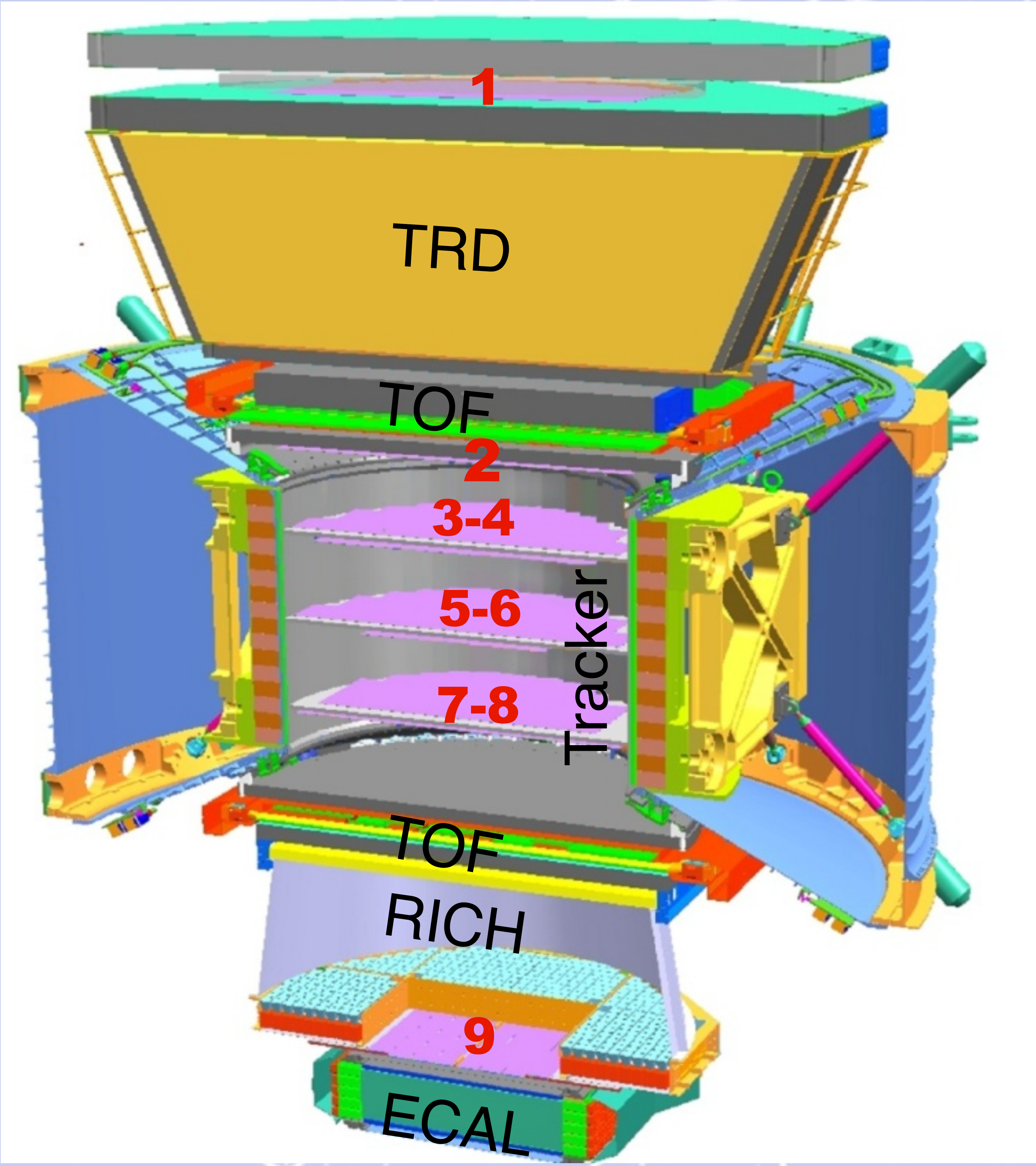
a) Minimo materiale nel TRD e nel TOF:
quindi il rivelatore NON diventa una sorgente di e^+ ;

b) Il magnete separa il TRD e ECAL cosi’ gli e^+ prodotti nel TRD sono deviati e non entrano nell’ECAL:
in tal modo il “rejection power” del TRD e dell’ ECAL sono independenti;

c) “Matching” dell’impulso dai 9 piani del Tracker con le misure di energia dell’ ECAL.

La precisa identificazione delle particelle si ha combinando le risposte dei diversi sotto rivelatori (ridondanza ...utile anche per eventi rari)





Ulteriori dettagli sui rivelatori di AMS-02

saranno/sono stati

forniti durante la visita

(vedi appendice)

Performance del rivelatore AMS-02 sulla ISS

L'esperimento AMS-02 sta operando senza particolari problemi.
In oltre 50 mesi di attivita' ha raccolto piu' di 70 miliardi di particelle.

Ogni anno , si raccolgono circa 16×10^9 eventi
che in 10-20 anni saranno $160\text{-}320\times10^9$.

Questa capacita' AMS-02 fornisce una sensitivita' senza precedenti per la ricerca di nuova fisica.

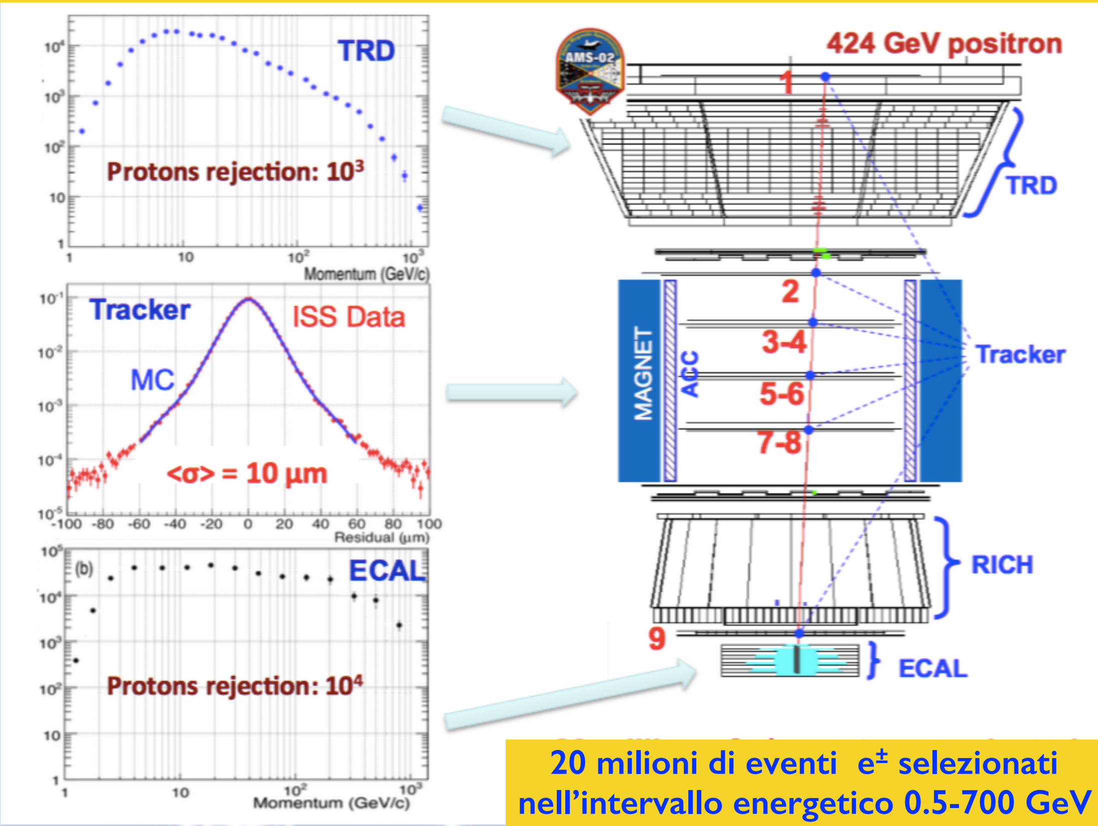
Risultati dell'esperimento AMS-02 e "physics expectations" dal maggio 2011 a settembre 2014

(Vedi appendice 13)

Risultati dell'esperimento AMS-02 e "physics expectations" aggiornati a Settembre 2016

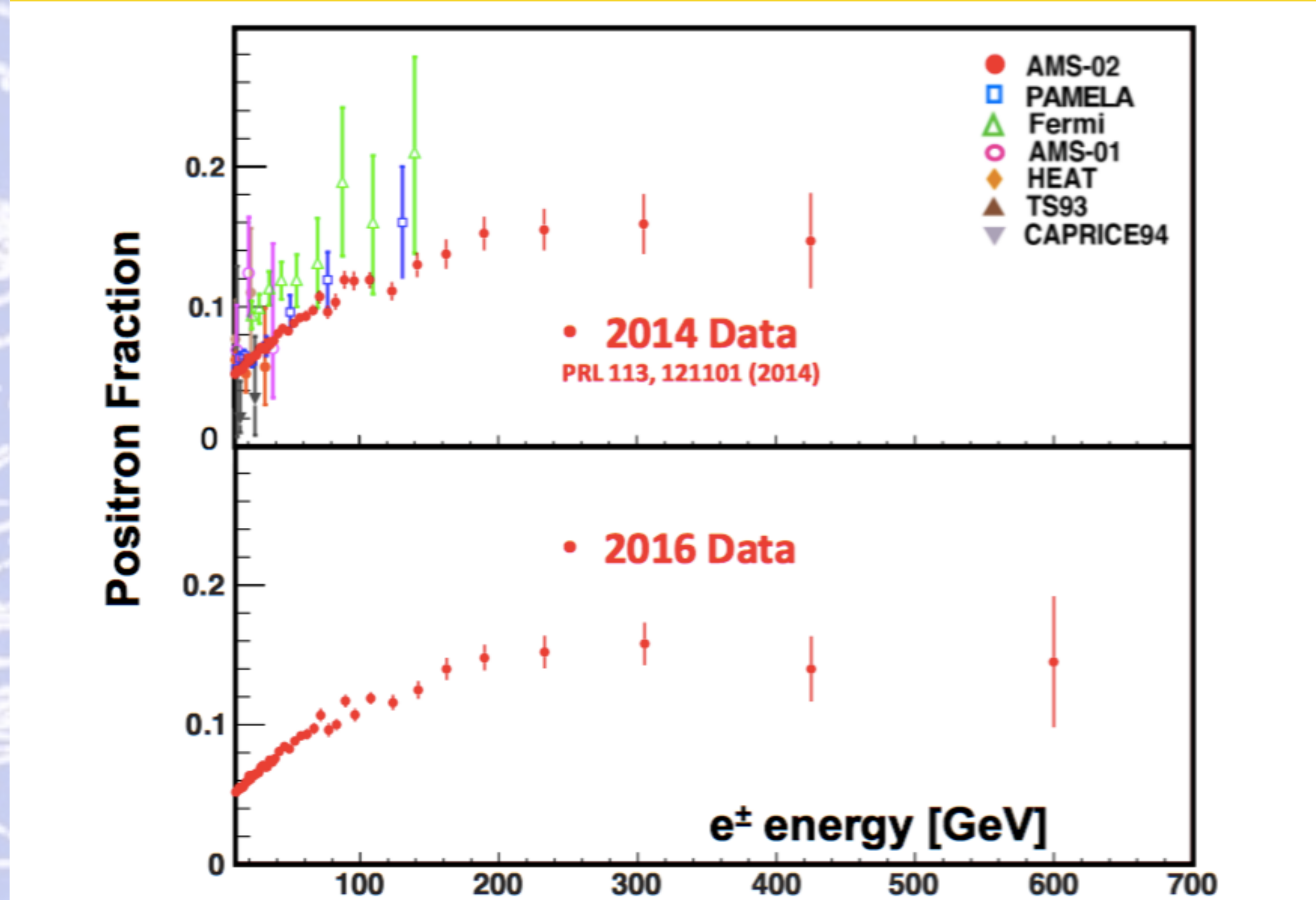
Positroni ed elettroni

Positron fraction analysis: dopo 5 anni di presa dati ⇔ $85 \cdot 10^9$ raggi

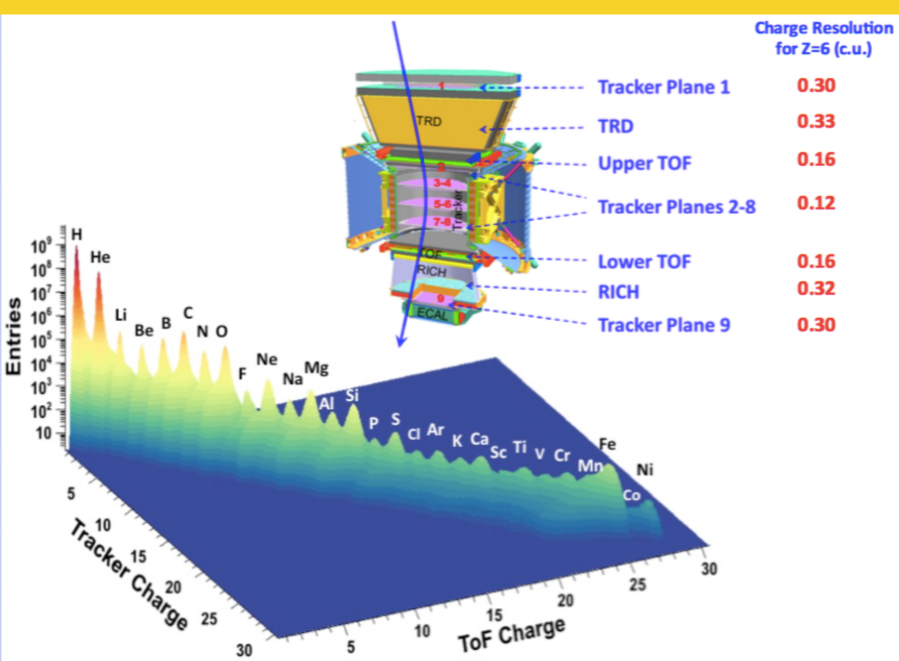


20 milioni di eventi $e^{\pm}$ selezionati nell'intervallo energetico 0.5-700 GeV

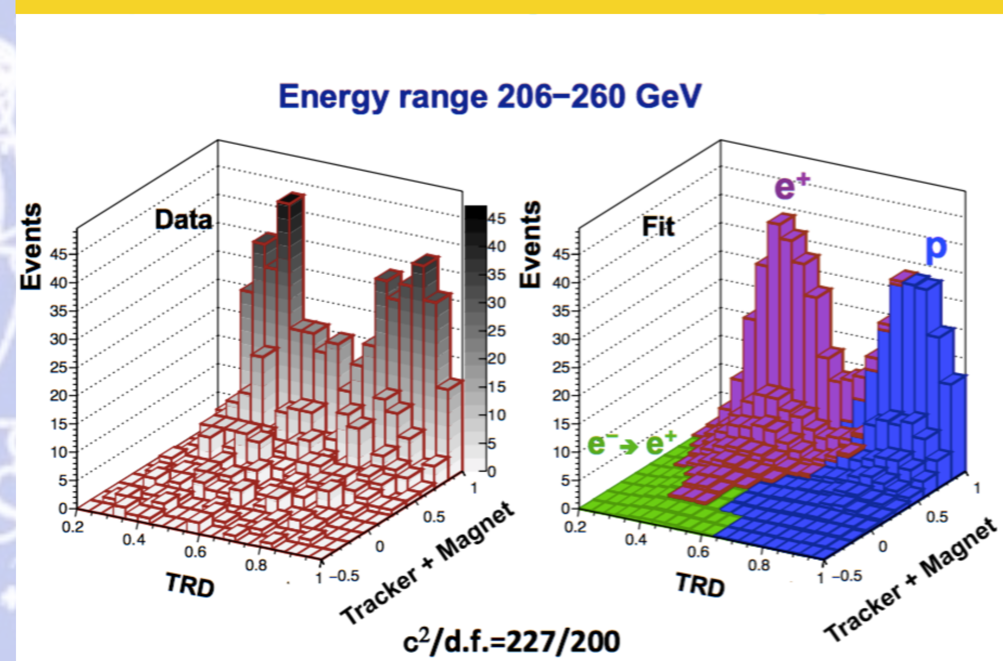
Rispetto al 2014: - intervallo energetico e' esteso a 700 GeV
- statistica e' aumentata da 11 a 20 milioni di $e^{\pm}$



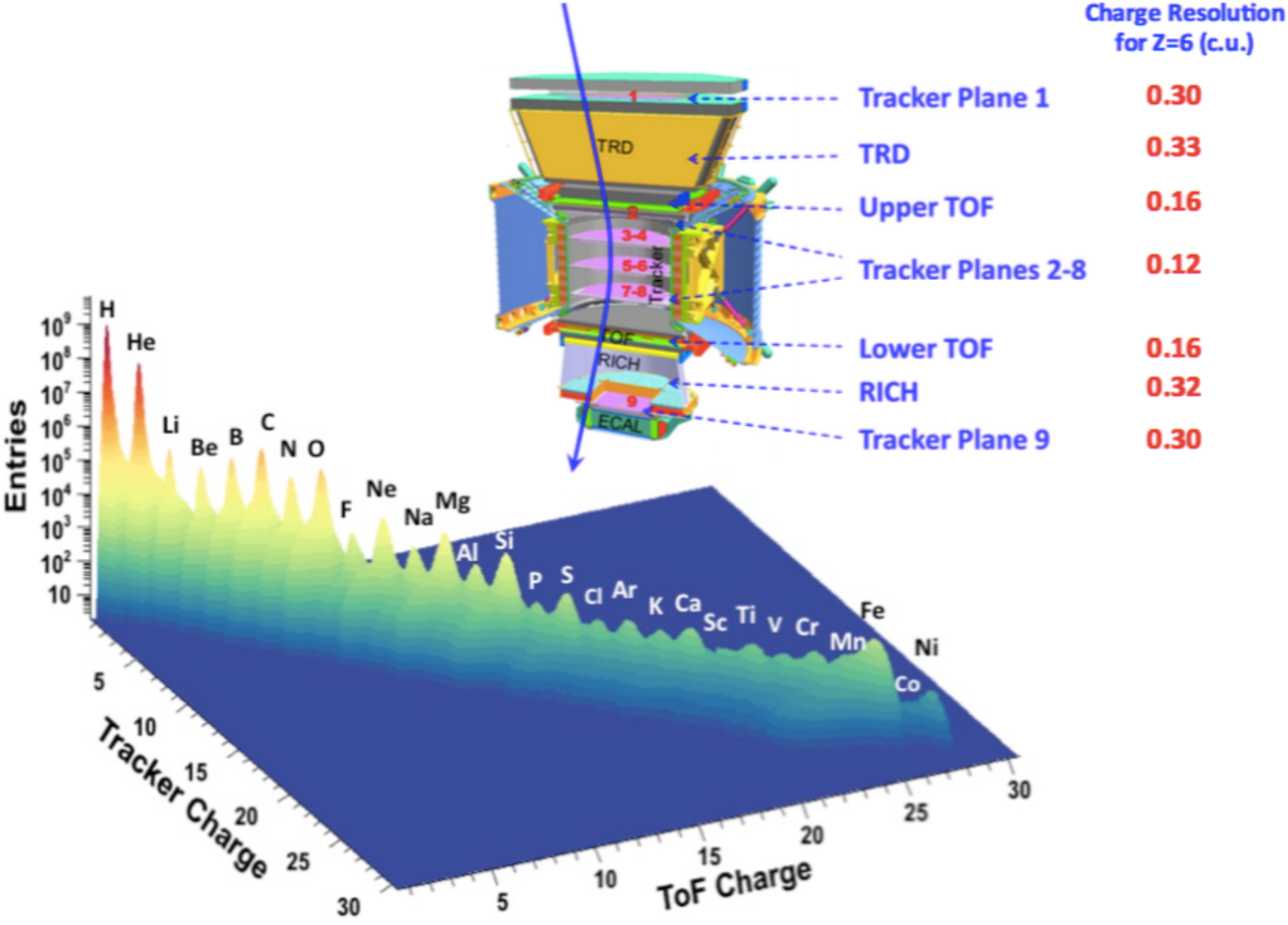
Misura della Carica: ridondanza



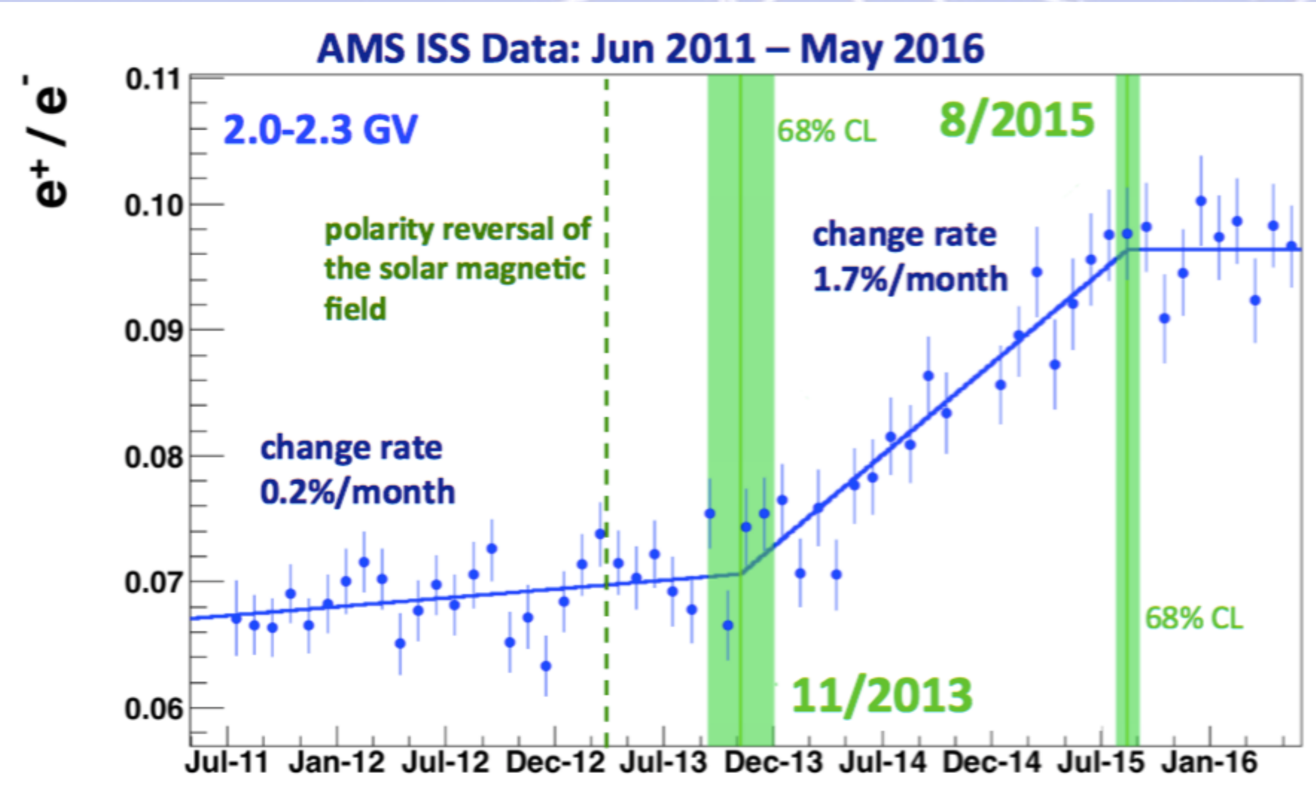
TRD Estimator: - chiara separazione tra positroni e protoni



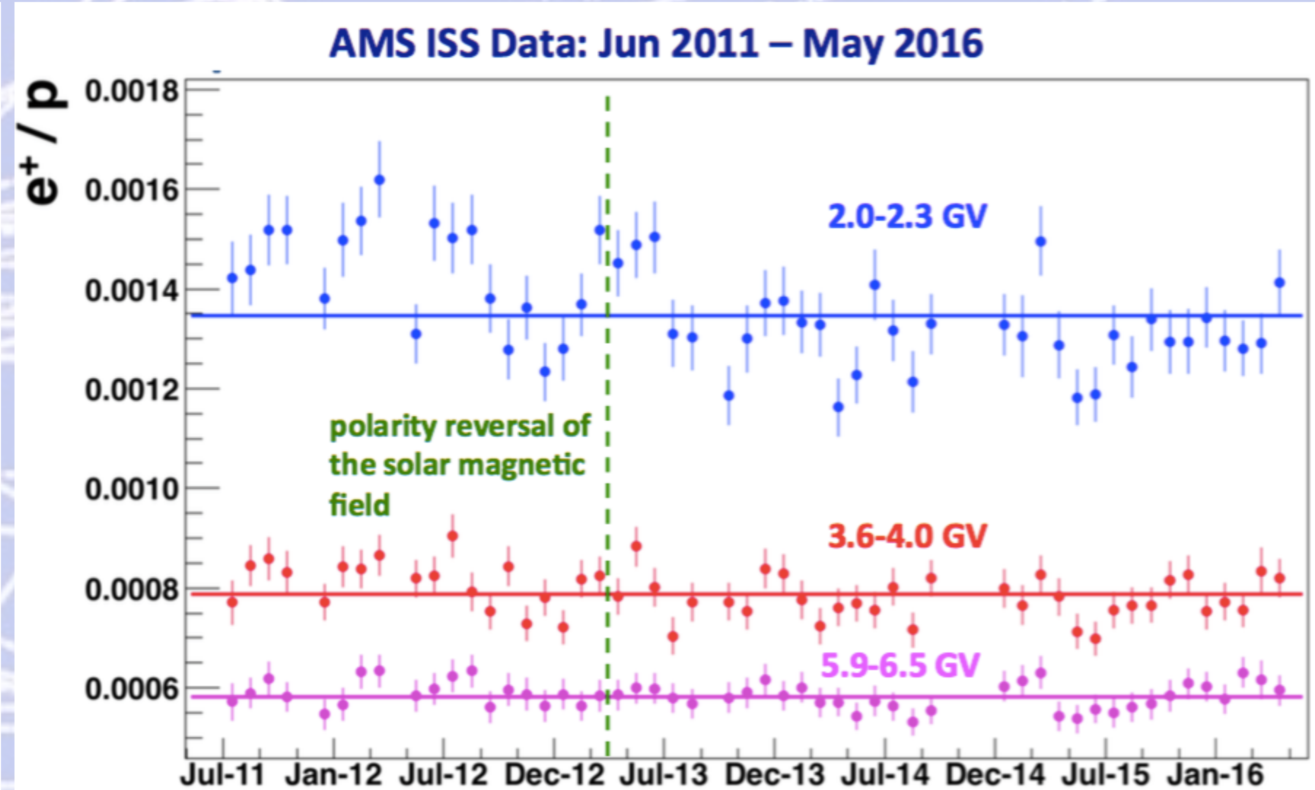
Multiple Measurements of Charge



Ciclo solare: inversione del campo magnetico solare



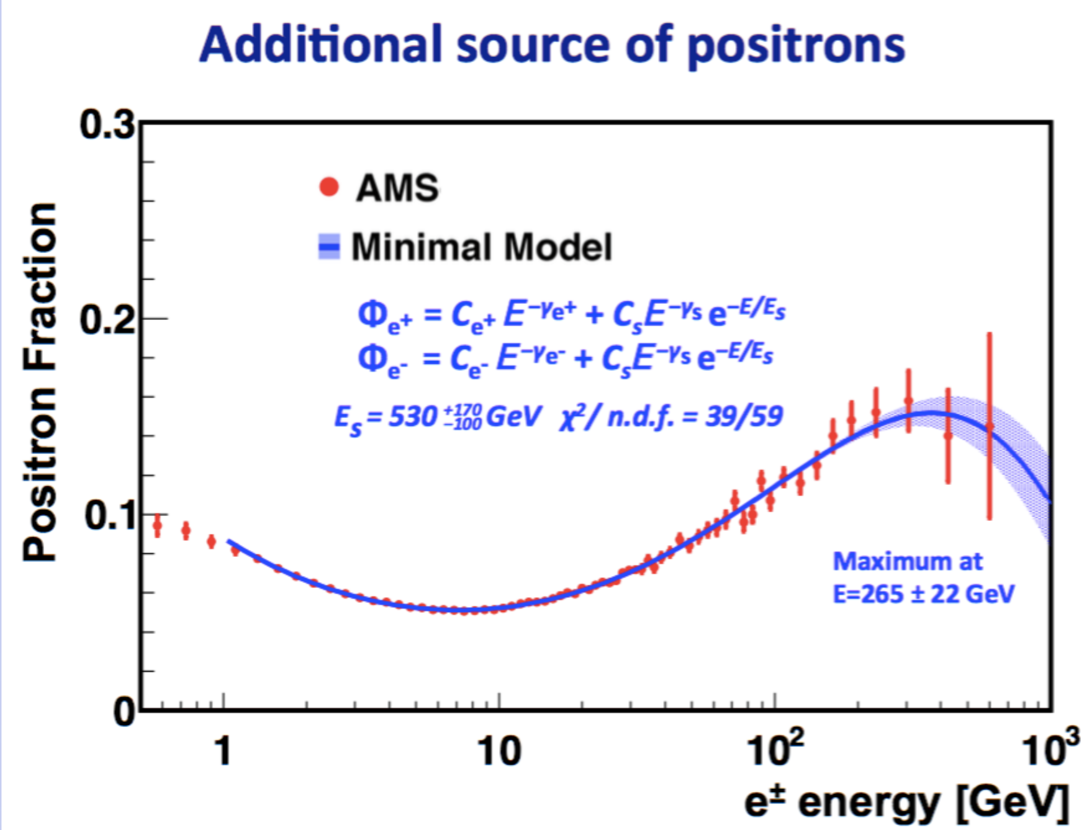
- After the reversal of the solar magnetic field in 03/2013 it takes (8 ± 1.5) month till this has a visible effect on the e^+/e^- ratio.
- It takes (21 ± 1) month to stabilize the e^+/e^- ratio again.



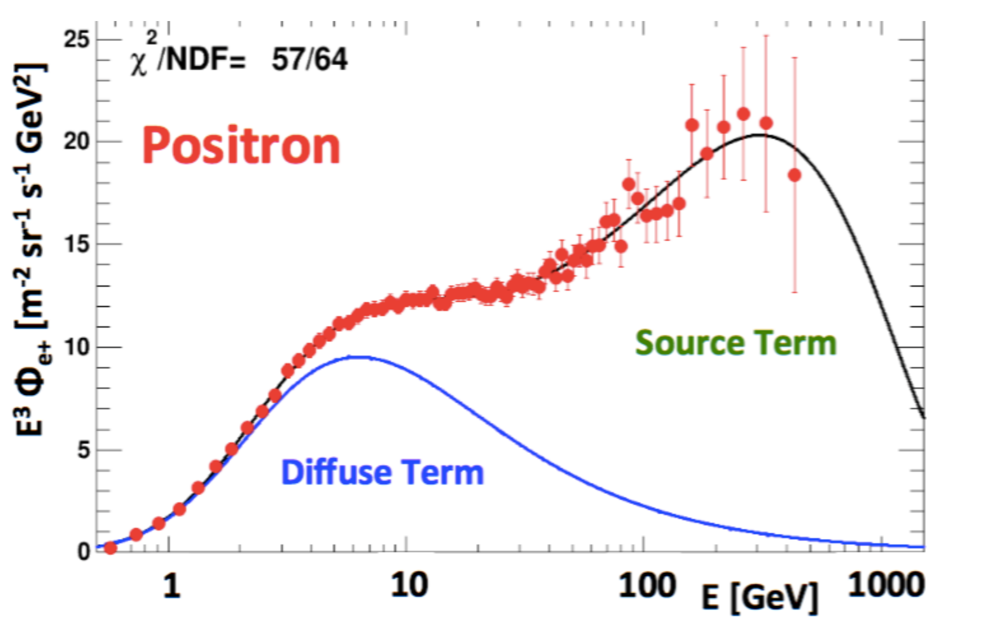
- The e^+/p ratio does not show large variations as a function of time.
- The full power of the AMS high precision data sets can only be explored after time dependent effects are extracted and the data can be used to constrain the local interstellar spectra.

AMS ed il monitoraggio continuo intorno alla Terra

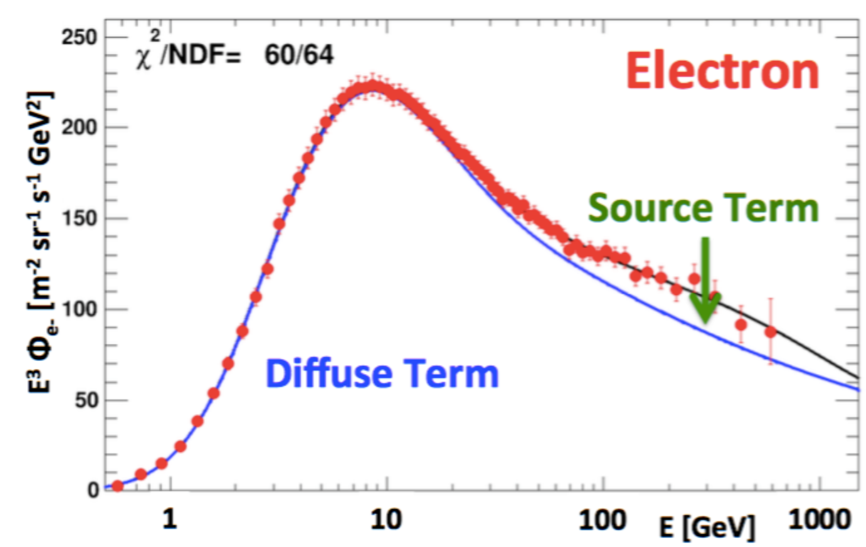
Positroni ed elettroni: lo spettro (1)



The Positron Flux has no sharp structures and is dominated at high energies by the source term.



The source term parameters are constrained from the positron flux fit.



The Electron Flux
- has no sharp structures and is dominated by the diffuse term.
- is consistent with a charge symmetric source term.

$$\Phi_{e+}(E) = \frac{E^2}{\hat{E}^2}\left[C_{e+}\hat{E}^{\gamma_{e+}} + C_s\hat{E}^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

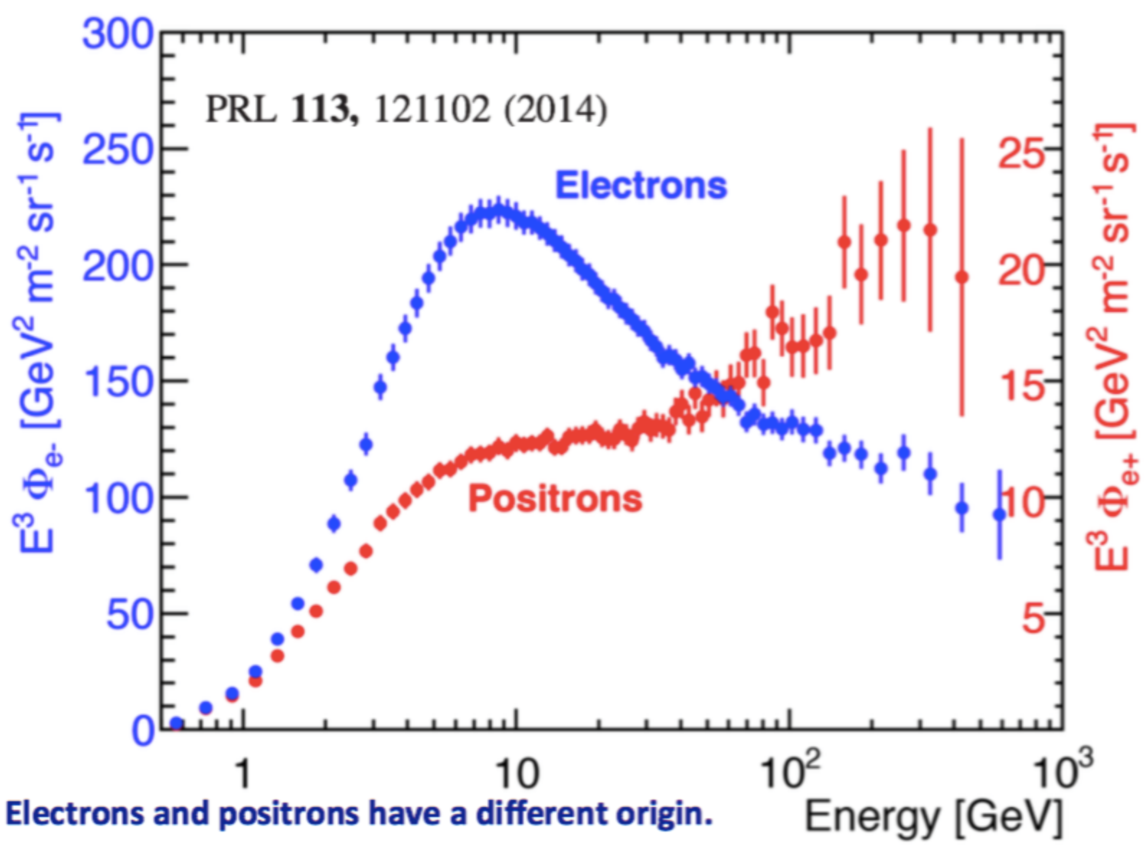
with $E_s = 530$ GeV from the $e^+/(e^+ + e^-)$ fit and $\hat{E} = E + \Psi$ as the energy scale of the LIS

The spectral index of the diffuse term has to become energy dependent:

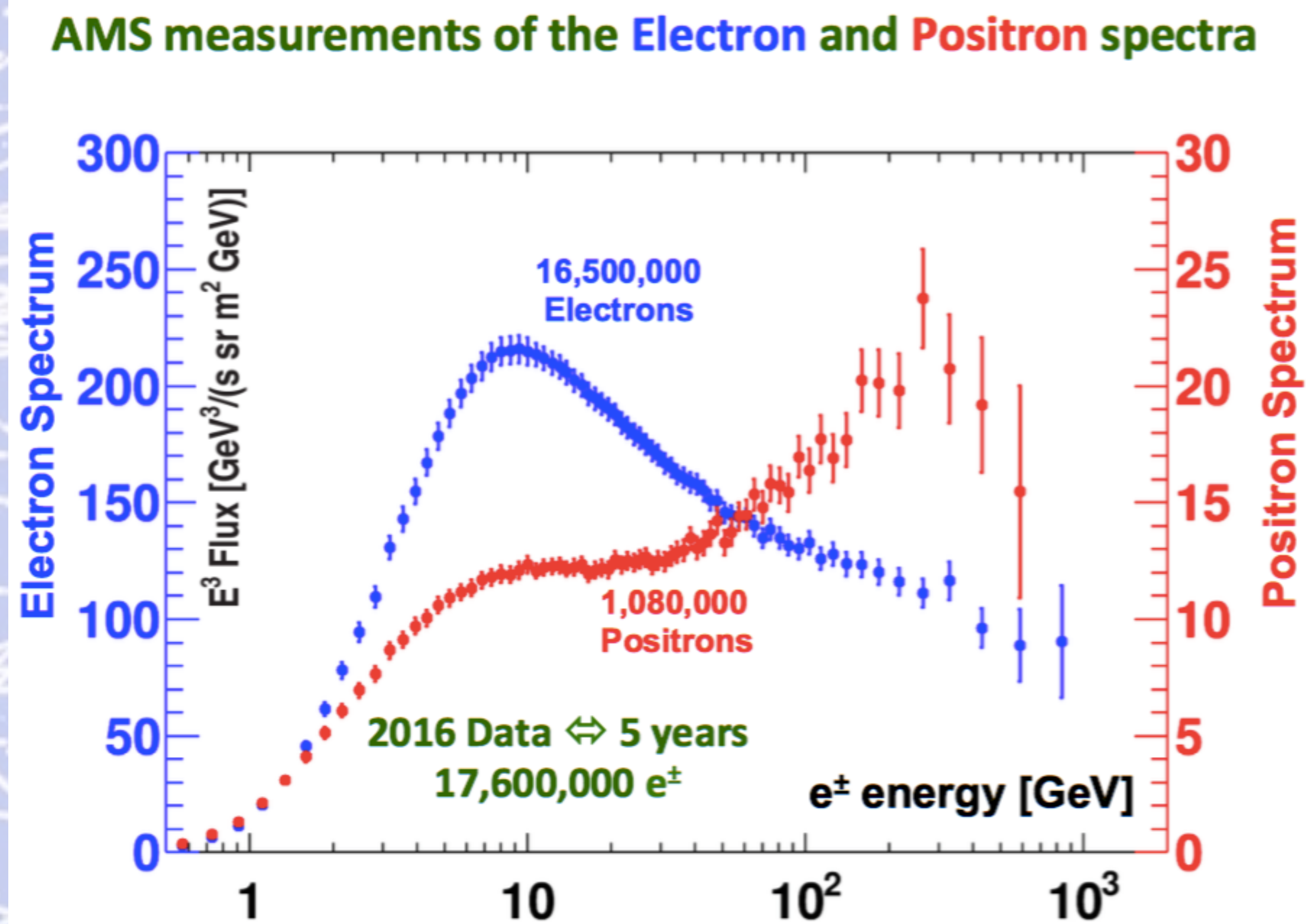
$$\Phi_{e-}(E) = \frac{E^2}{\hat{E}^2}\left[C_{e-}\hat{E}^{\gamma_{e-}(\hat{E})} + C_s\hat{E}^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

The source term parameters are constrained from the positron flux fit.

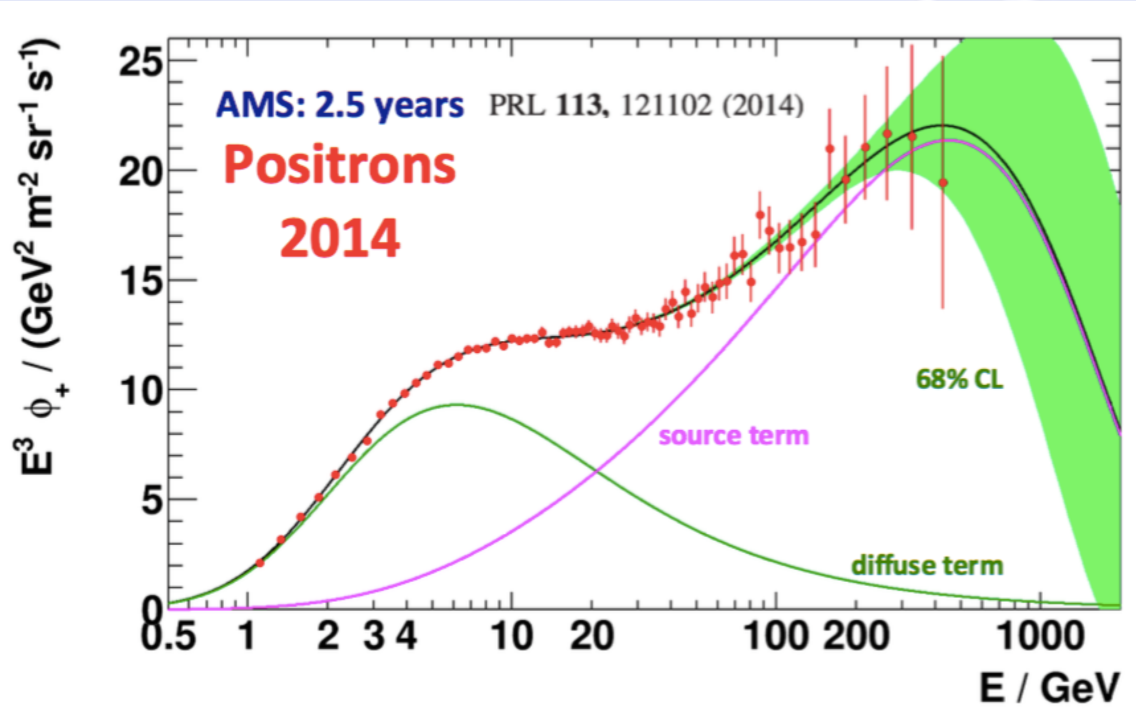
Positroni ed elettroni: lo spettro (3)



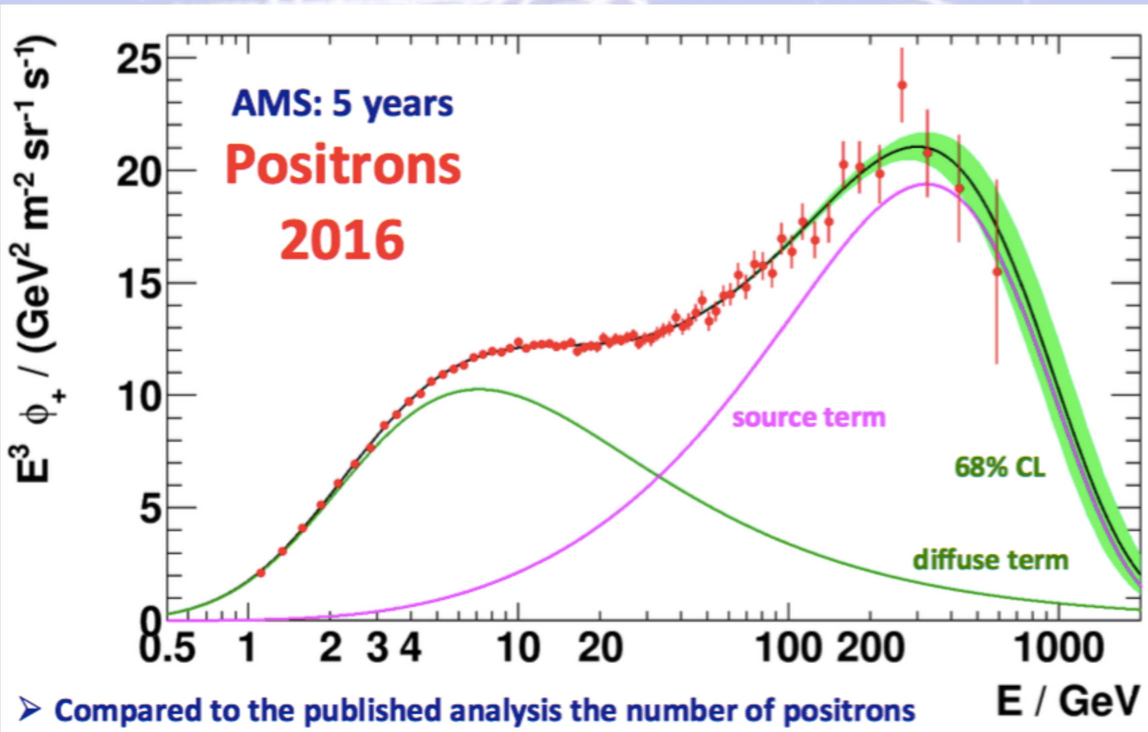
- Electrons and positrons have a different origin.
- A „Standard Model" to describe all our data does not exist.
- Therefore we have to use simple phenomenological models.



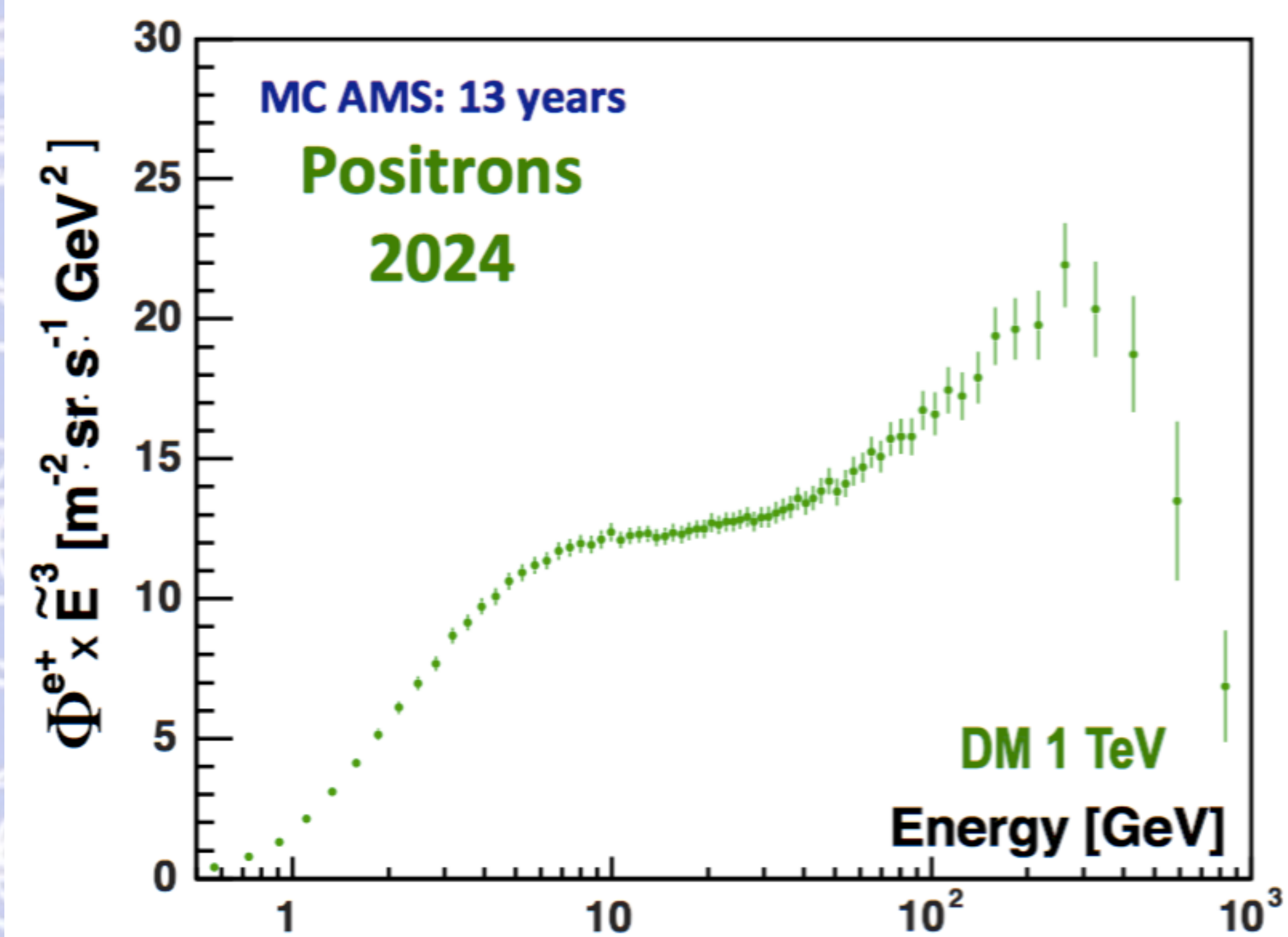
Positroni: dati e previsioni



- The AMS measurements are dominated by statistical errors for E>50 GeV.
- The energy range is limited up to 500 GeV.
- The significance of the energy cutoff in the source term is at the level of 2σ.

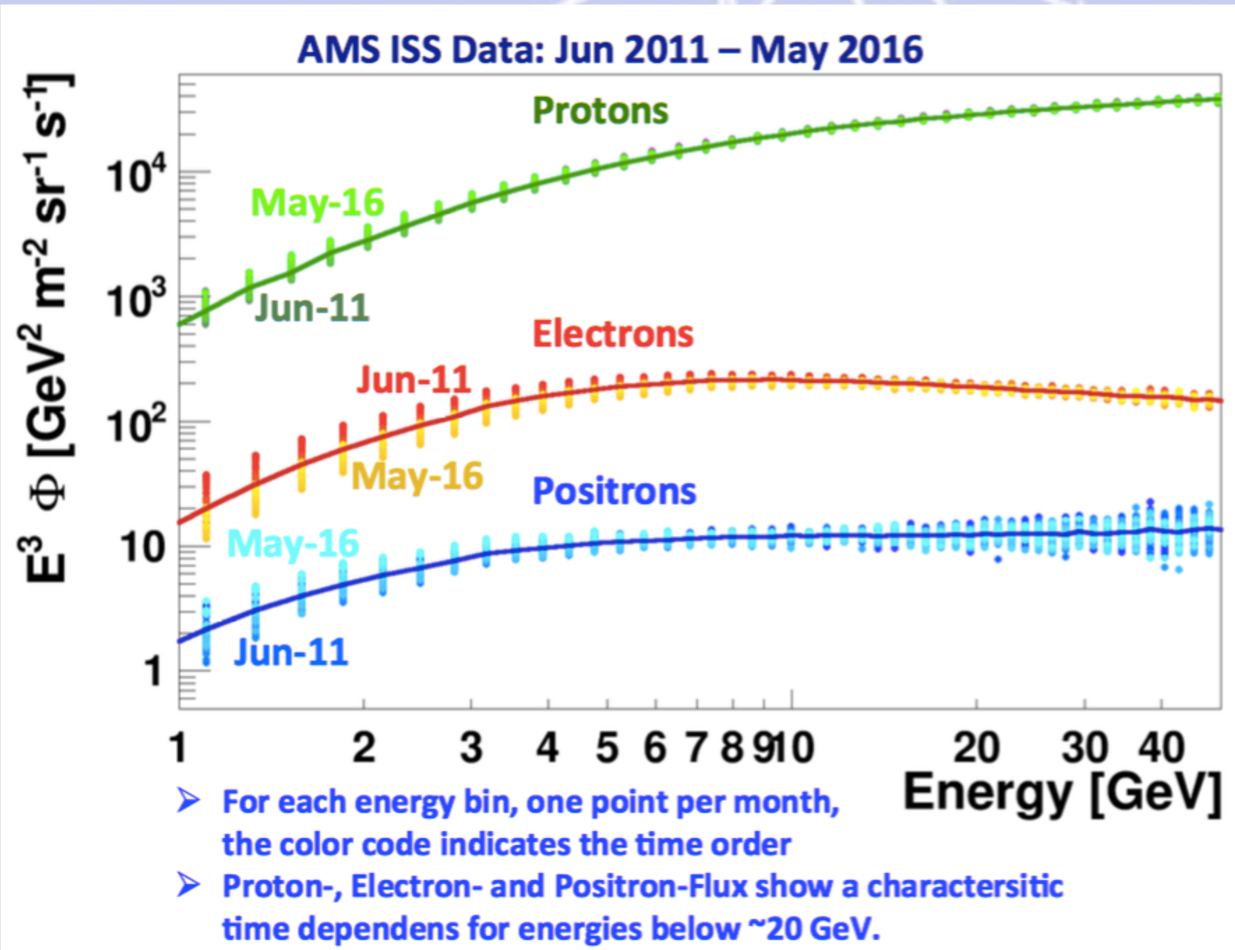


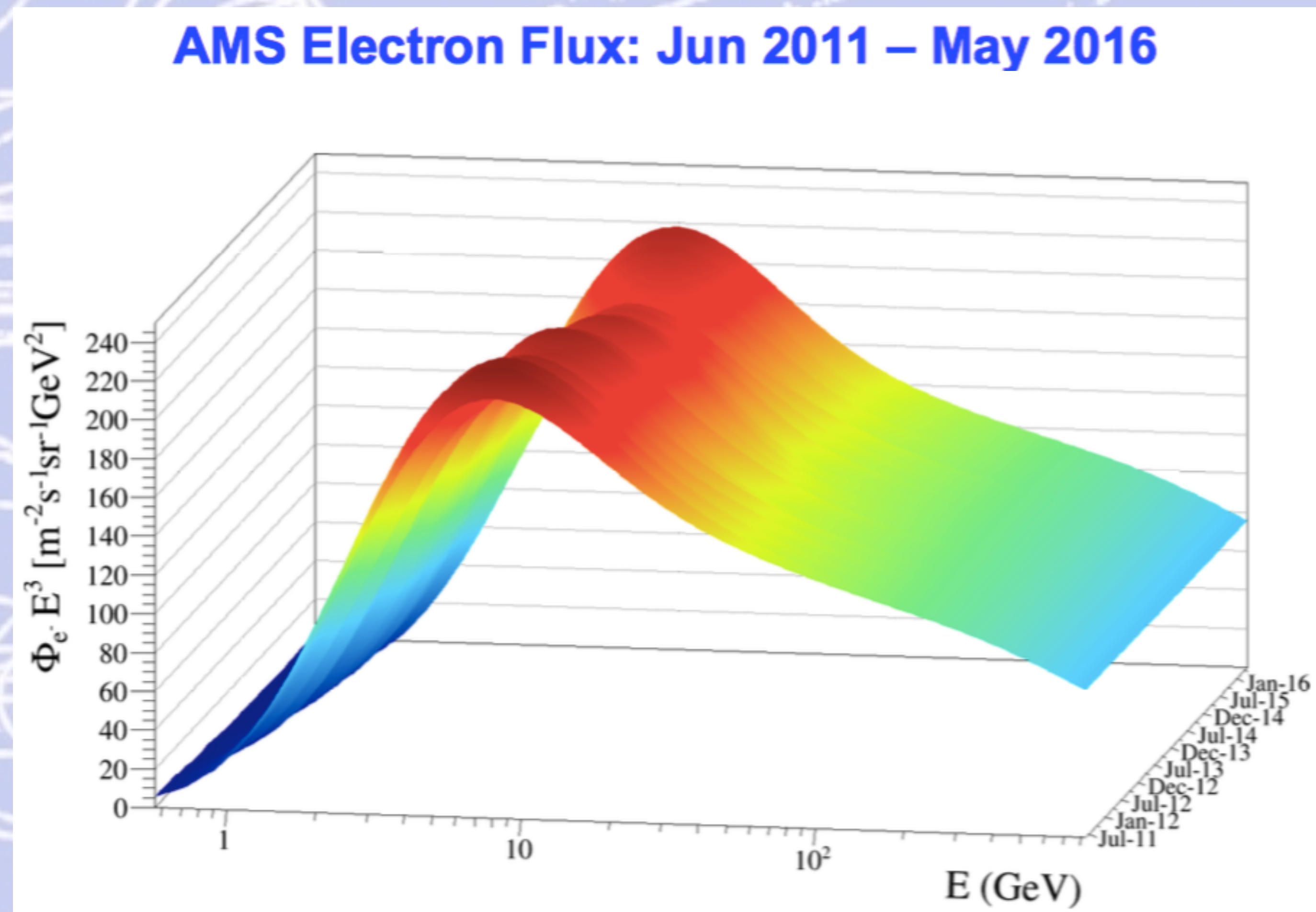
- Compared to the published analysis the number of positrons has been increased from 0.58 Million to 1.08 Million.
- The energy range has been extended up to 700 GeV.
- The significance of the energy cutoff of the source term has increased to 3σ.



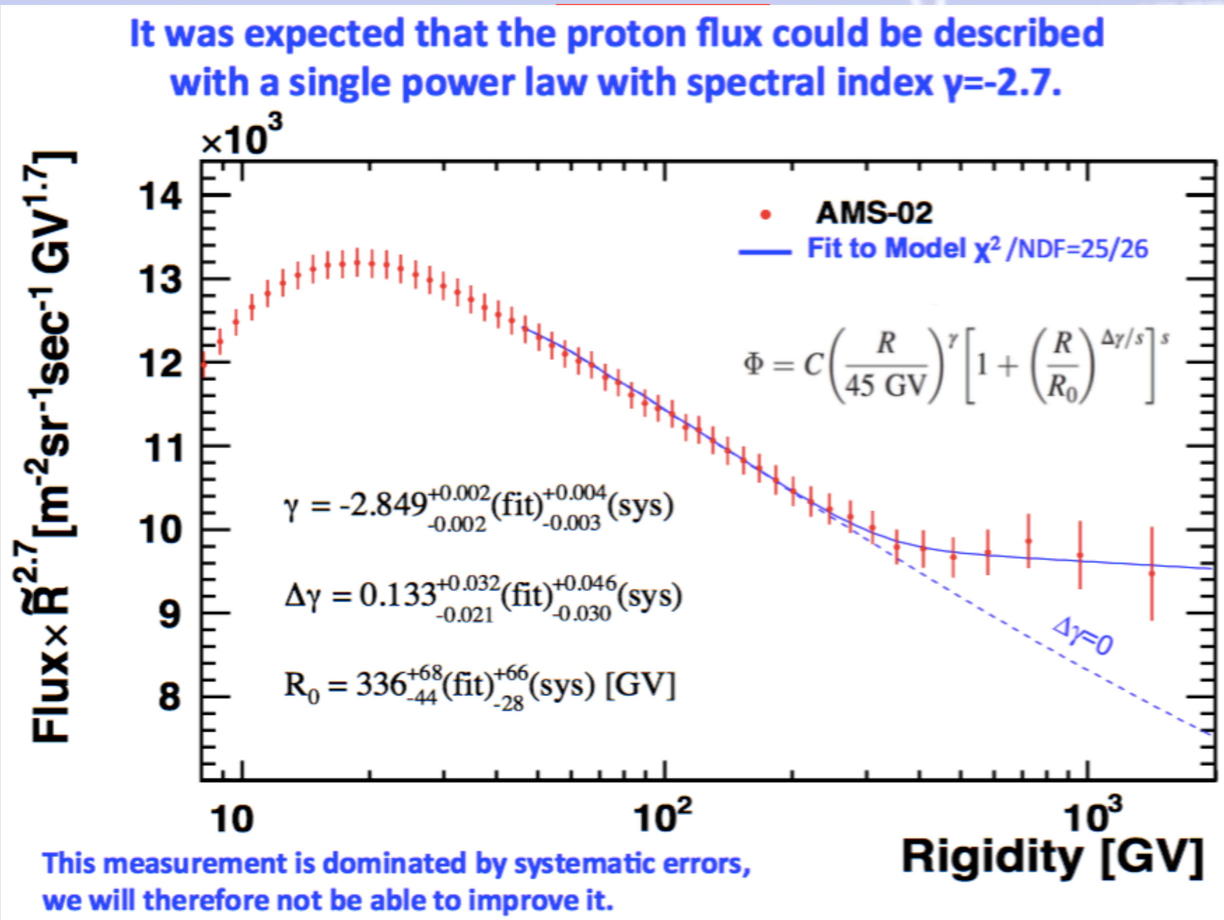
- The significance of the energy cutoff of the source term will have increased by 2024 to >5σ.

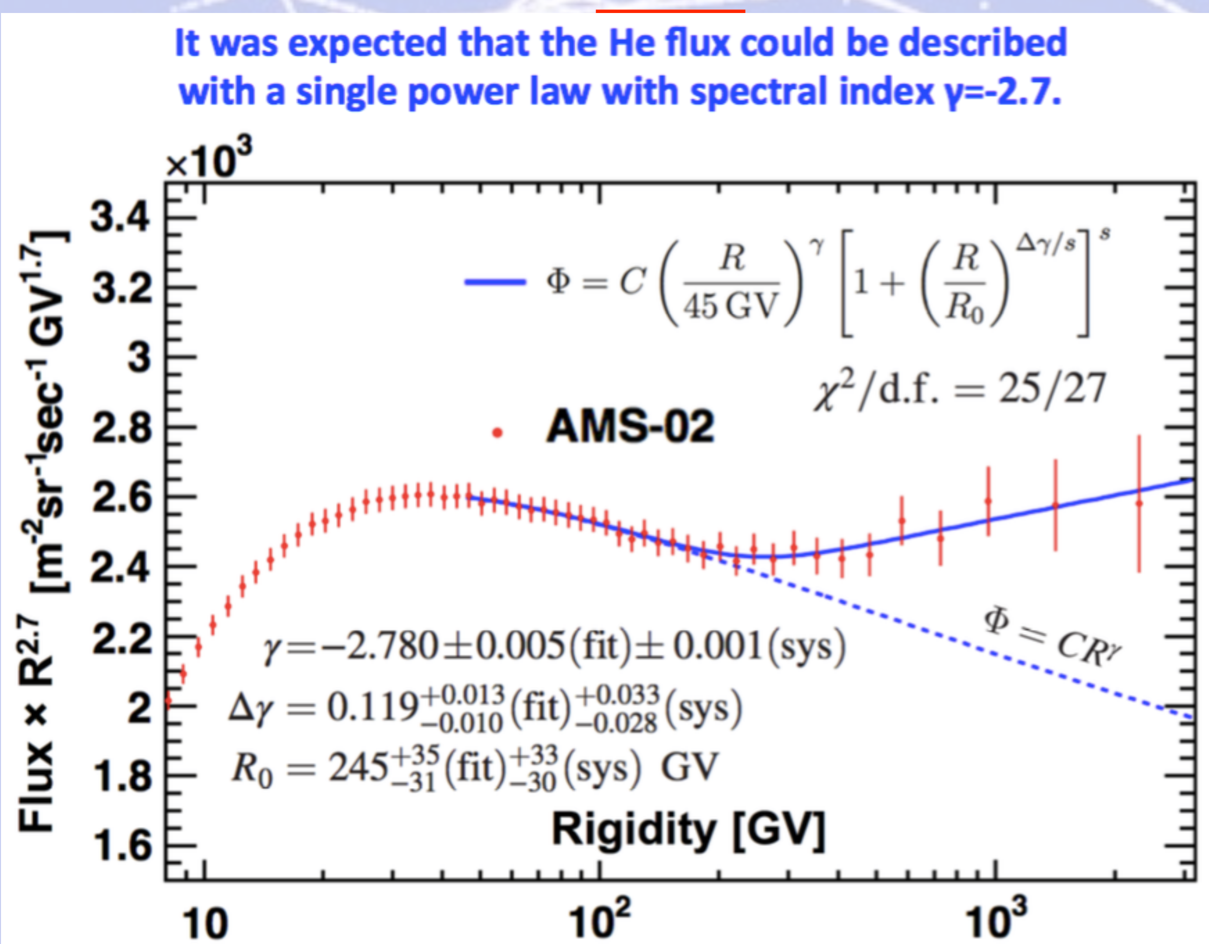
Positroni, elettroni e protoni: segnale e fondo

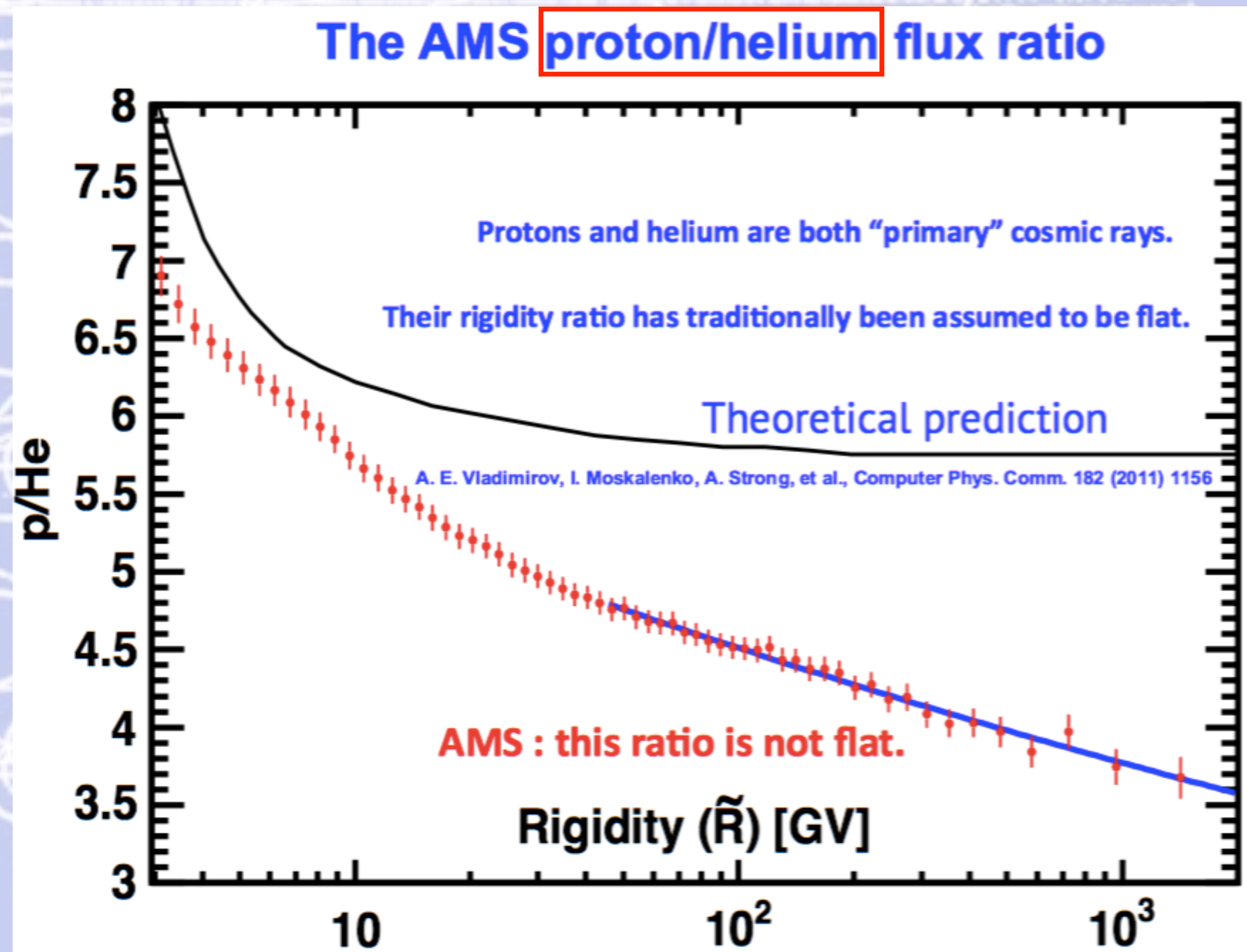




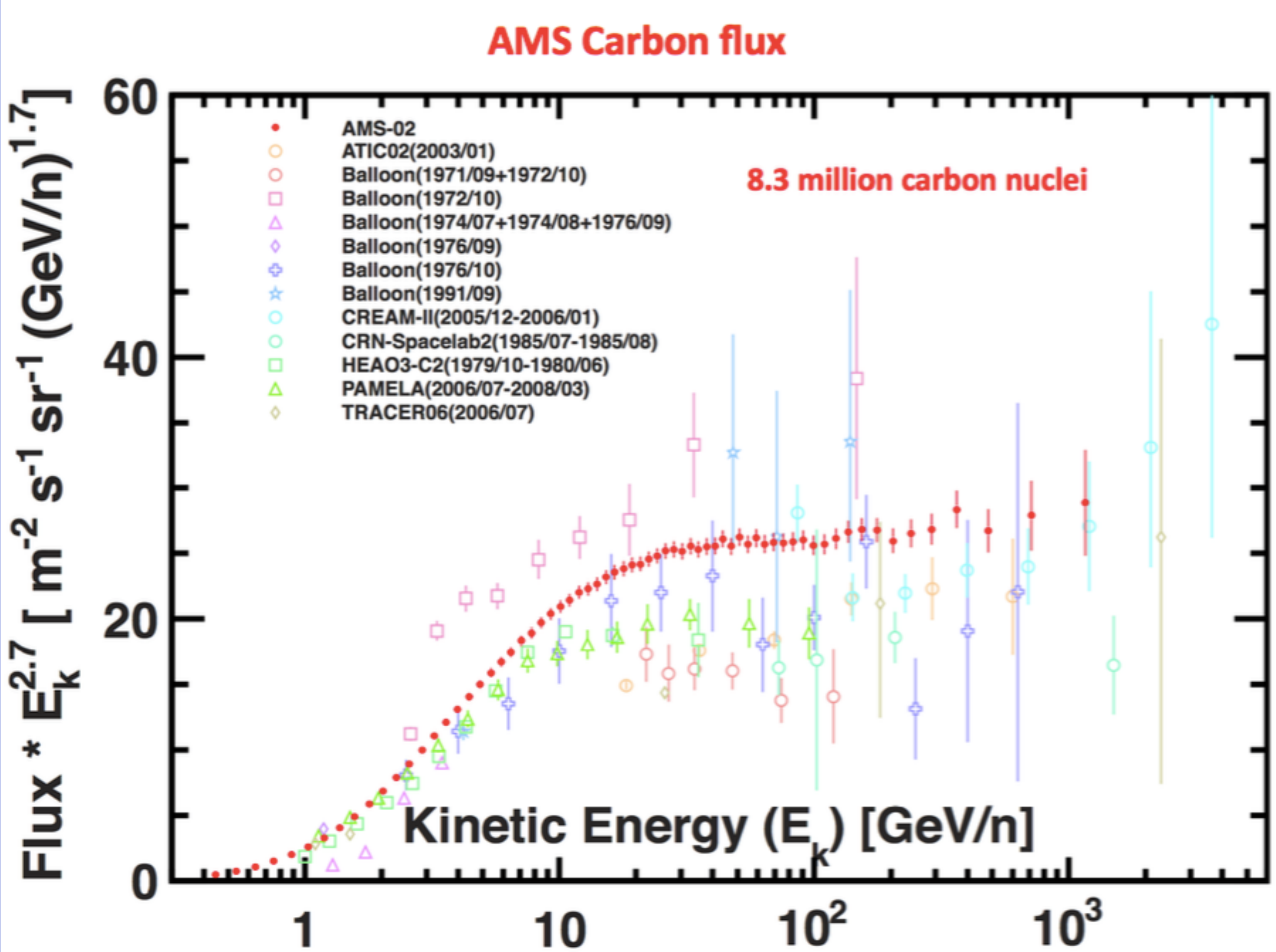
Protoni ed elio: flusso





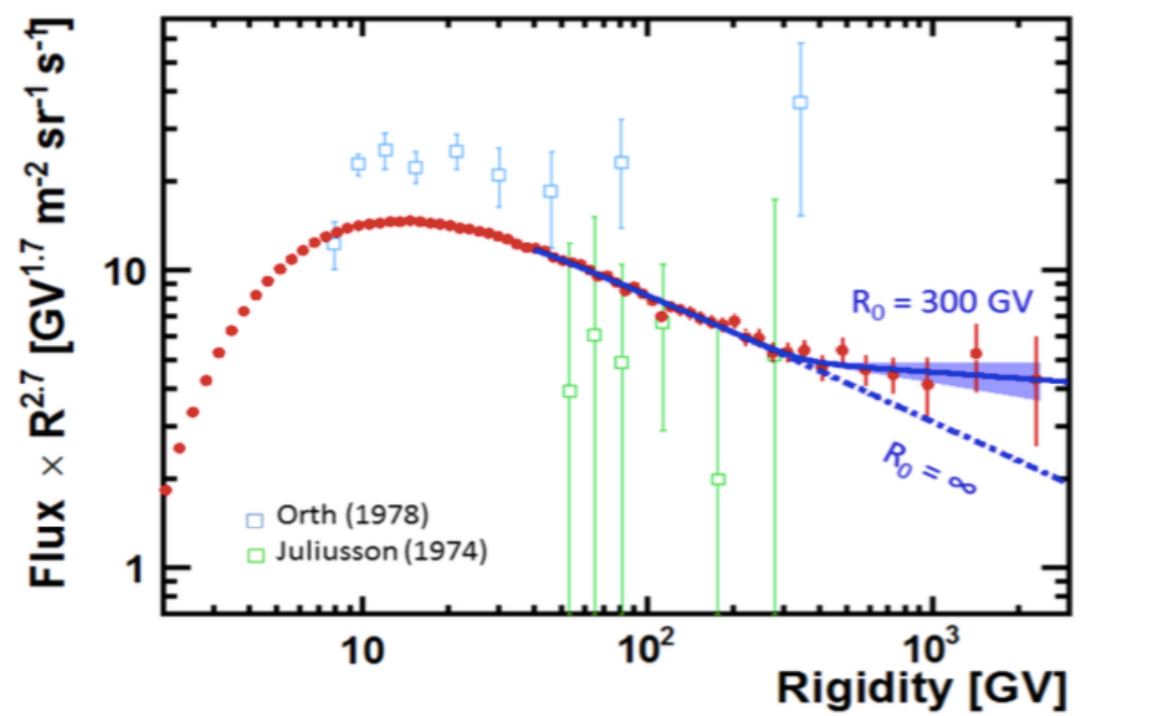


Carbonio e Litio: flusso



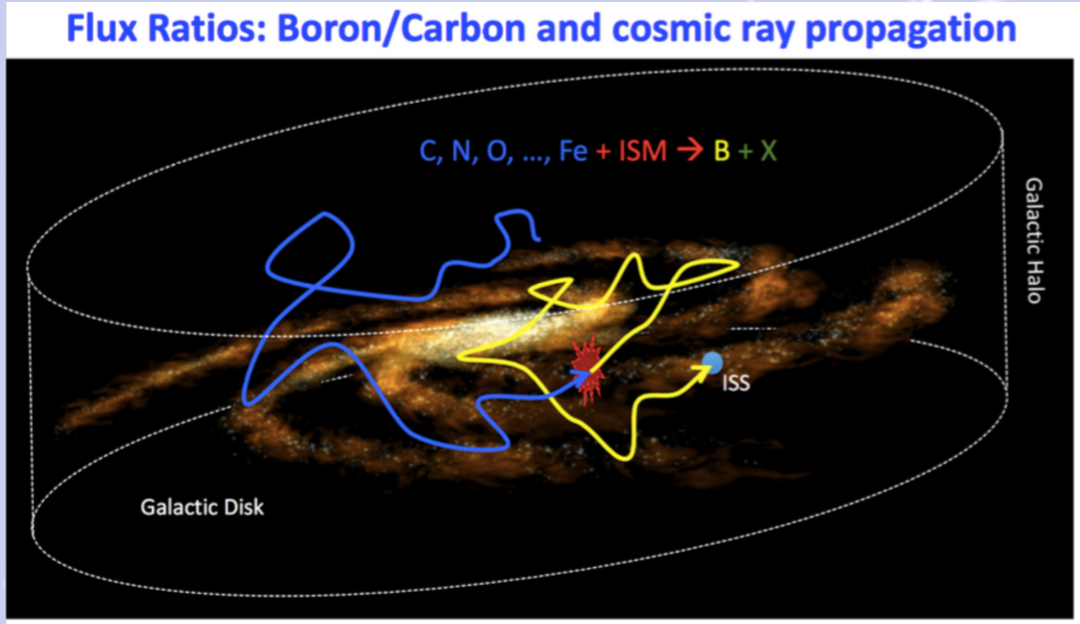
AMS Lithium flux

Up to now it was assumed that cosmic lithium is purely secondary in origin.
The AMS data show that either cosmic lithium has also a primary origin or the diffusion coefficient that describes the propagation of cosmic rays is rigidity dependent.

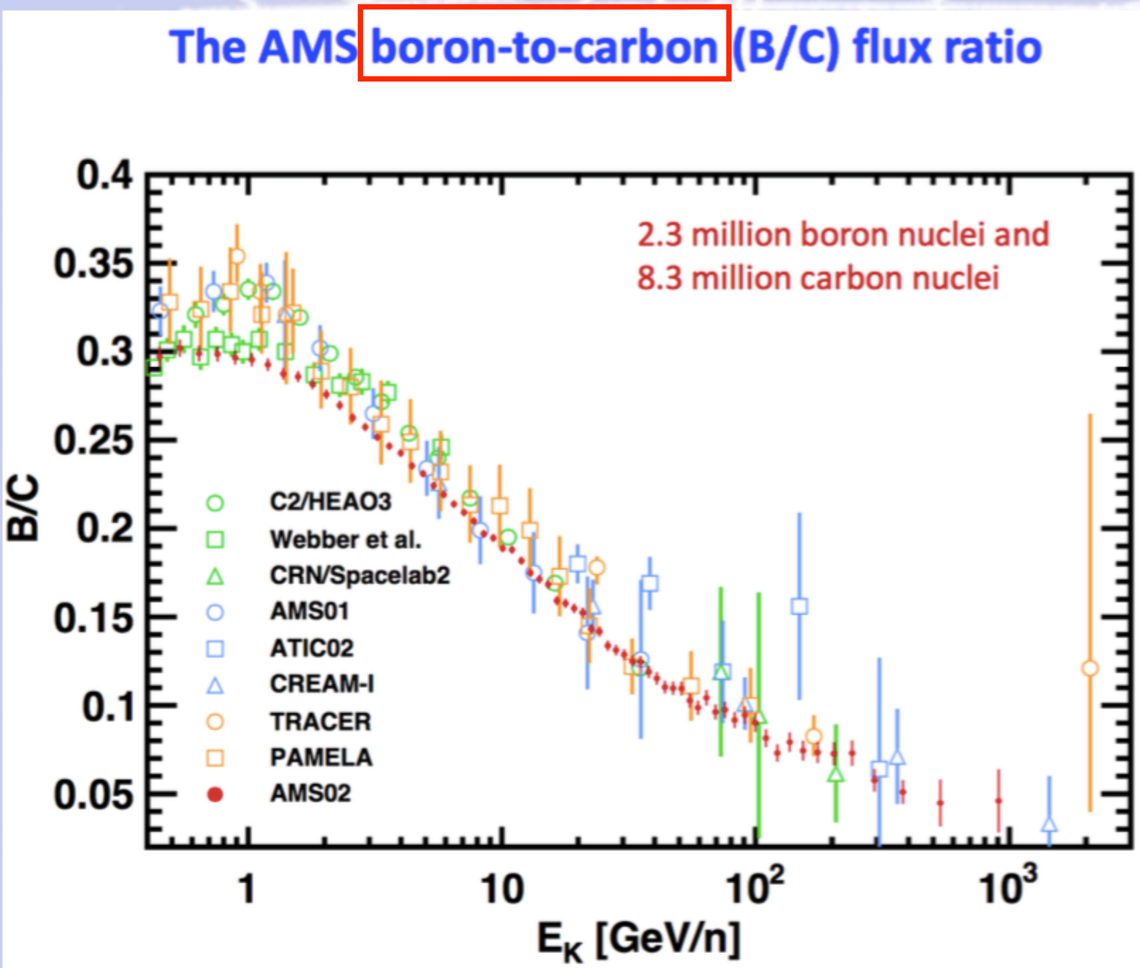


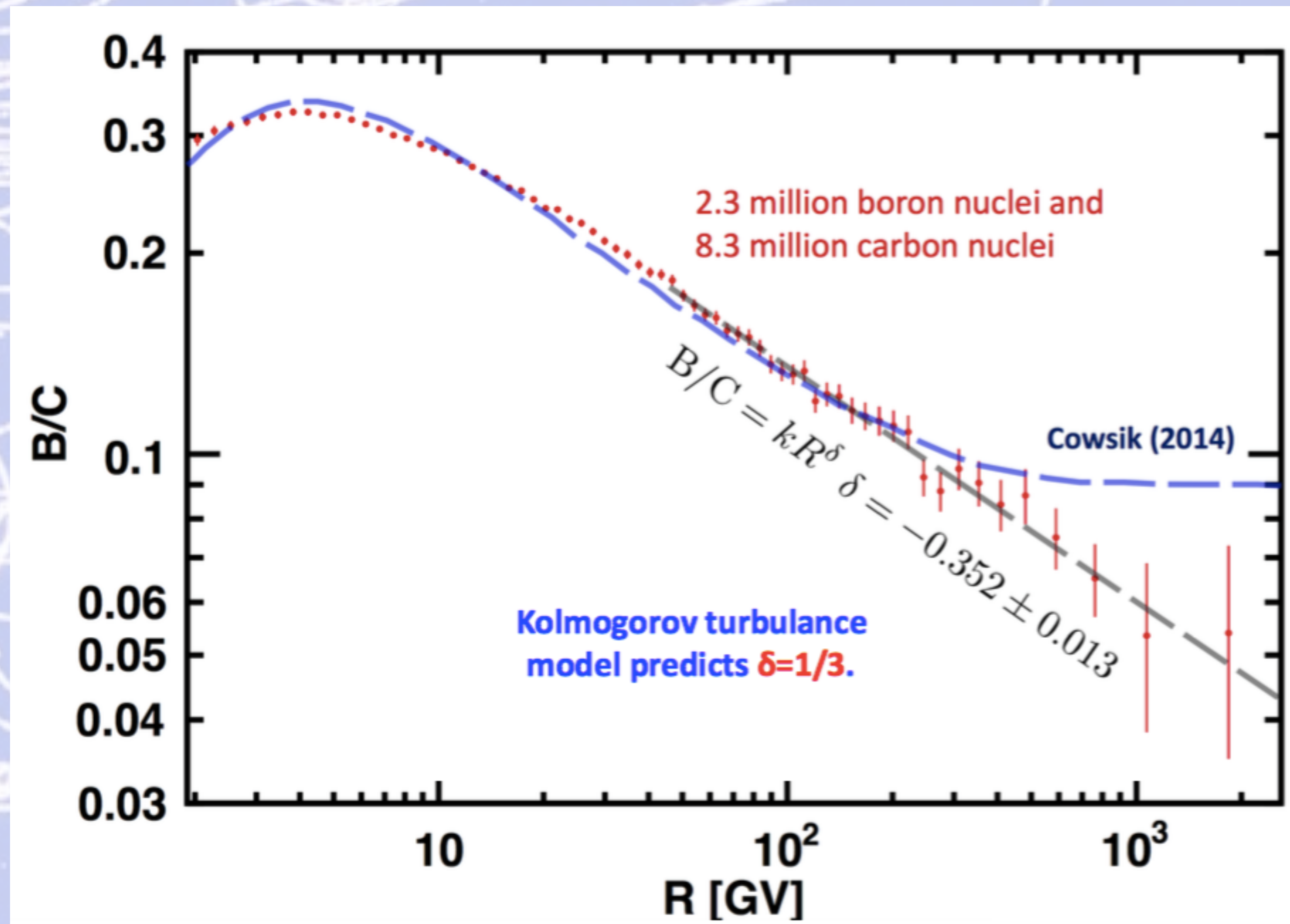
The AMS lithium flux fitted with a double power law $\Phi = C \cdot (R/45GV)^{\gamma} \cdot (1+(R/R_0)^{(\Delta\gamma/s)})^s$ (solid line, shaded region 1-sigma limits).

Boro/Carbonio: dati e previsioni



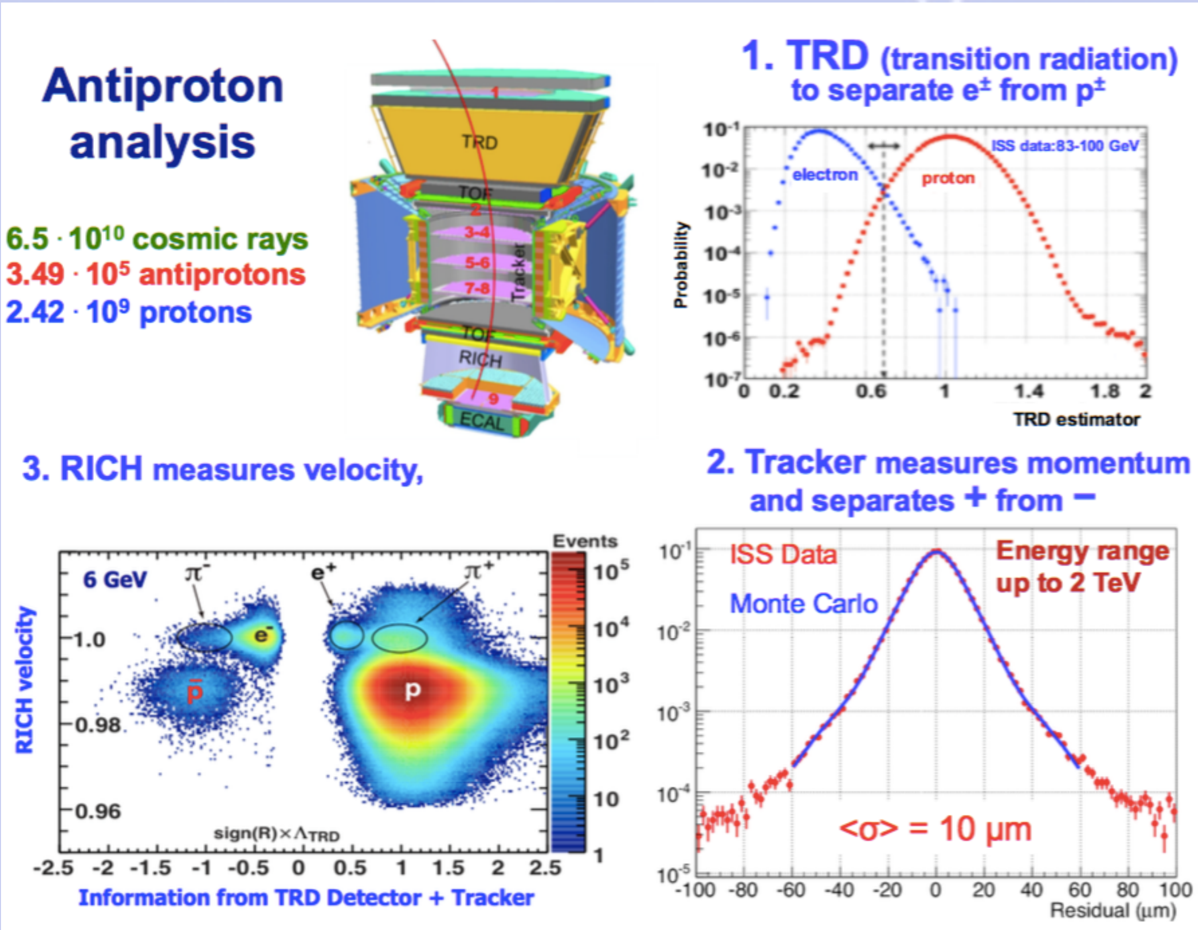
The boron-to-carbon ratio (B/C) is important in the determination of cosmic ray propagation. Boron is assumed to be produced from the collision of primary cosmic rays, such as carbon (C), with the interstellar medium (ISM), hence the B/C ratio provides information on cosmic ray propagation.

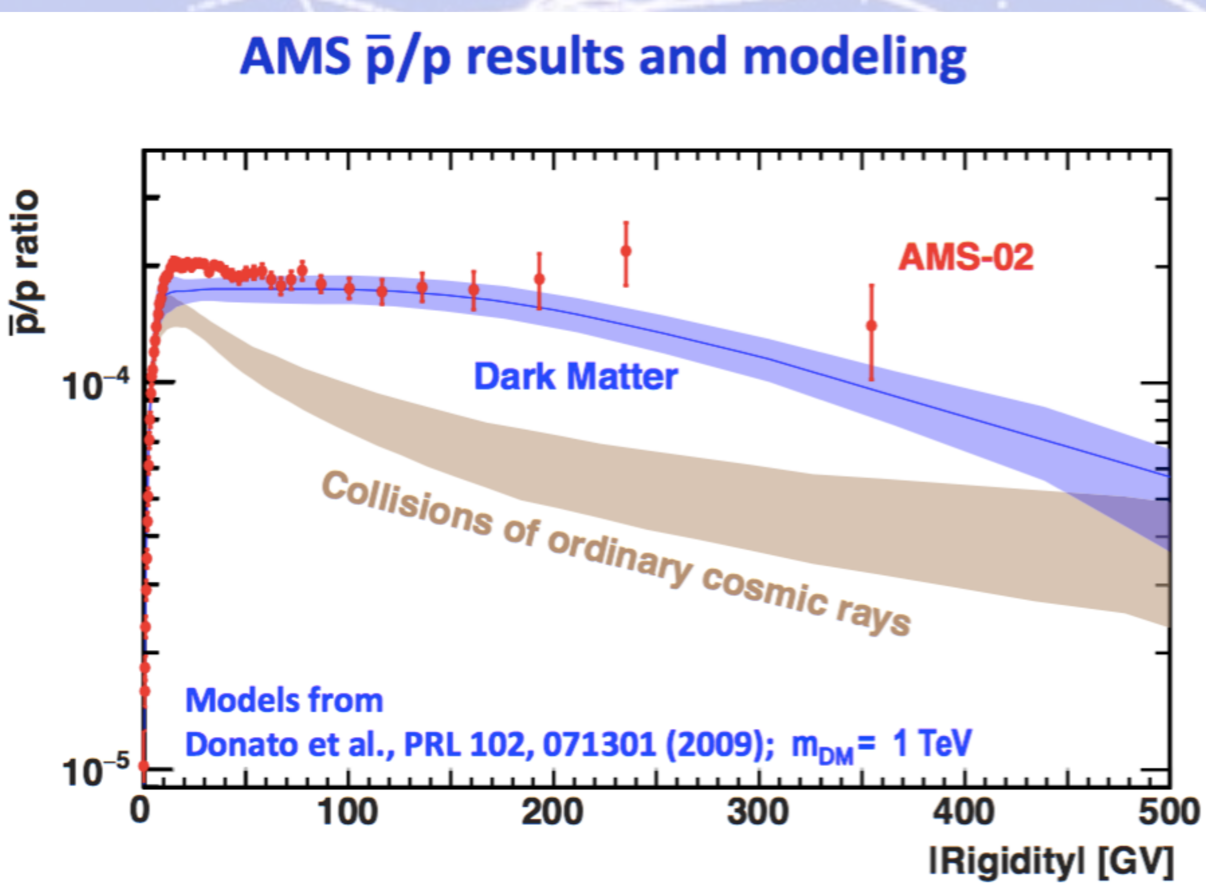


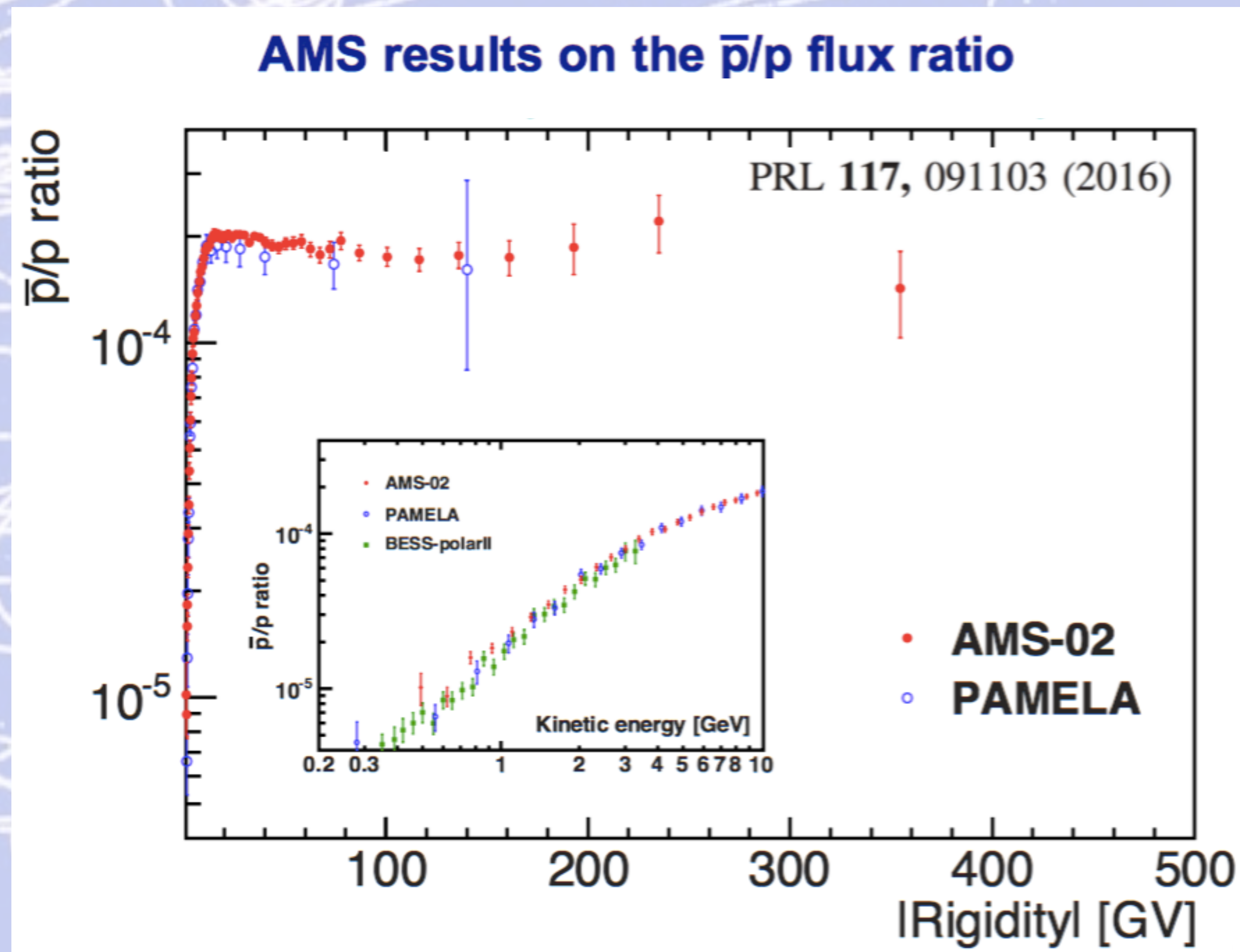


(Dettagli sui modelli teorici in appendice 6)

Protoni ed antiprotoni

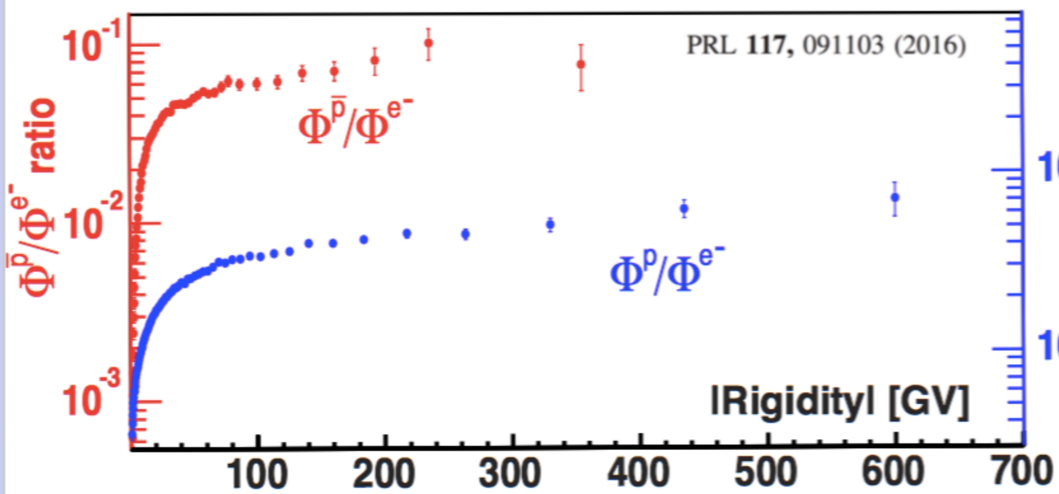






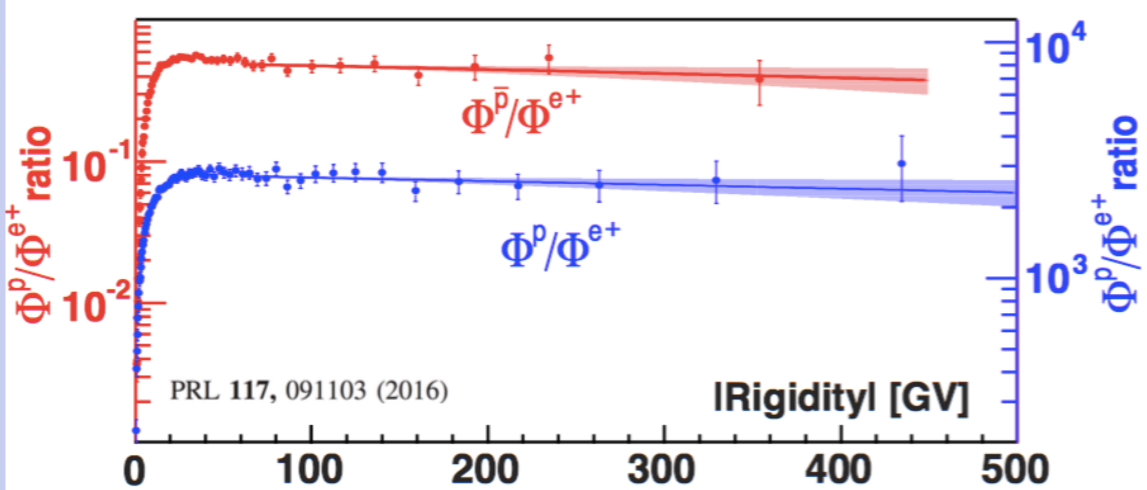
Dipendenza energetica dei flussi

Flux Ratios $\bar{p}/e^-$ and p/e^- are not energy independent in the interval 60–450 GV



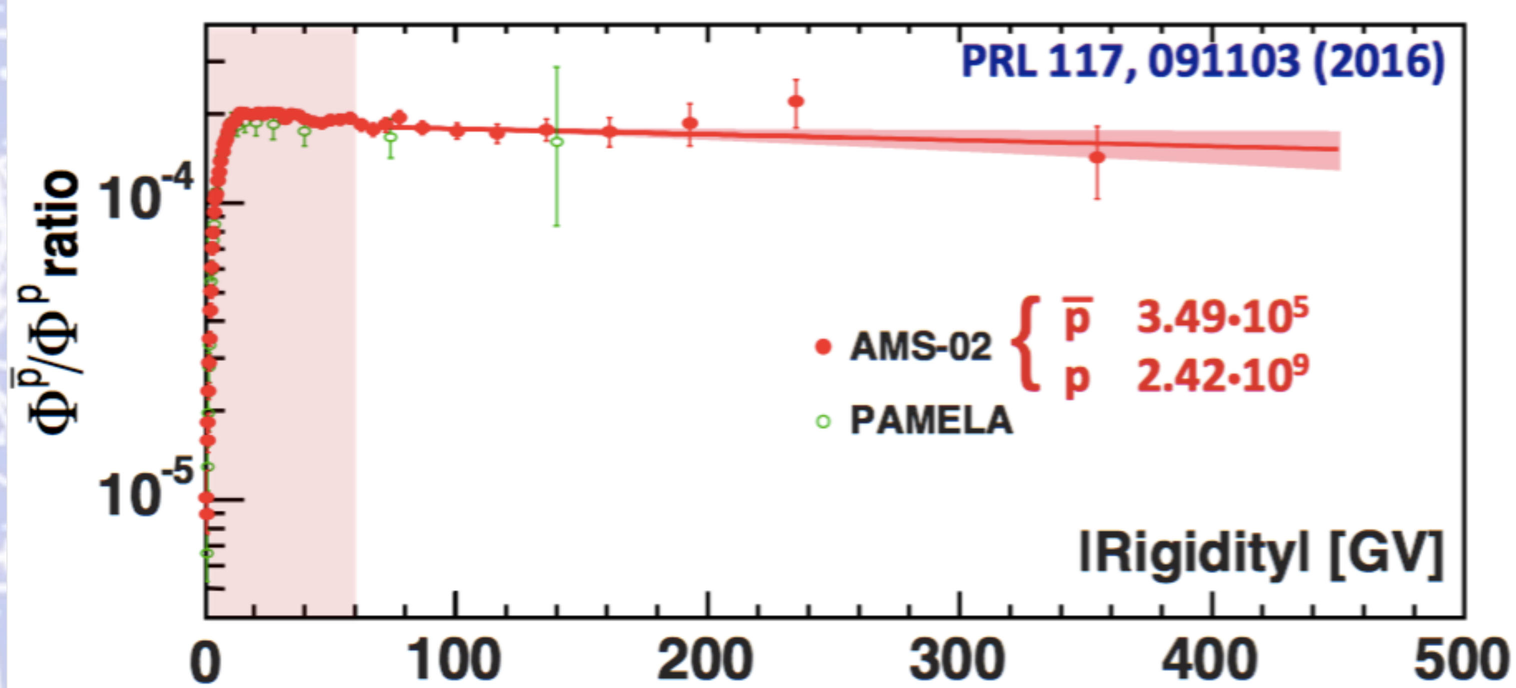
As expected: significant energy losses of e^- due to synchrotron radiation

Flux Ratios $\bar{p}/e^+$ and p/e^+ are also energy independent in the interval 60–450 GV

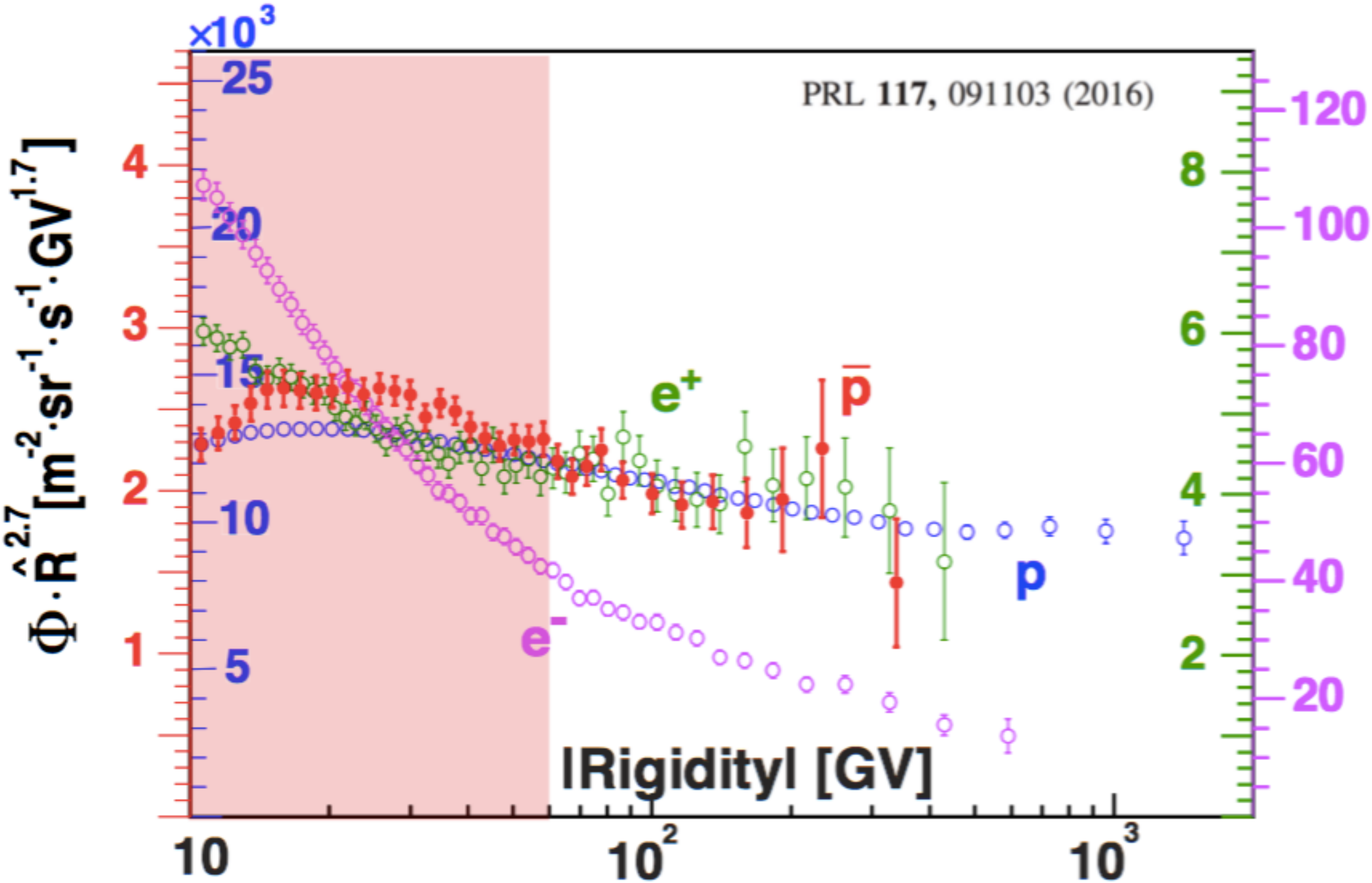


Unexpected Result

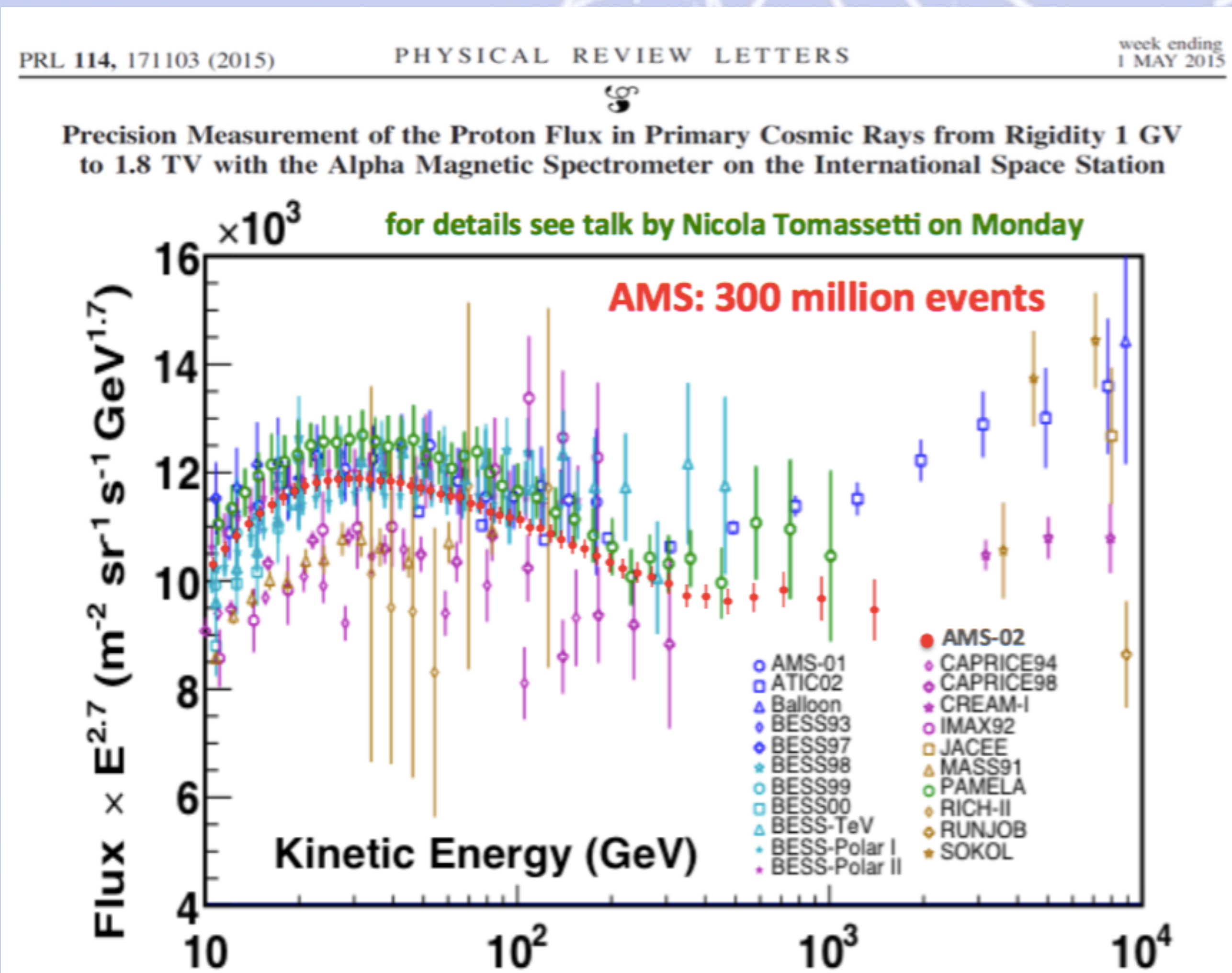
Flux Ratio of Elementary Particles $\bar{p}/p$ is energy independent above 60 GeV

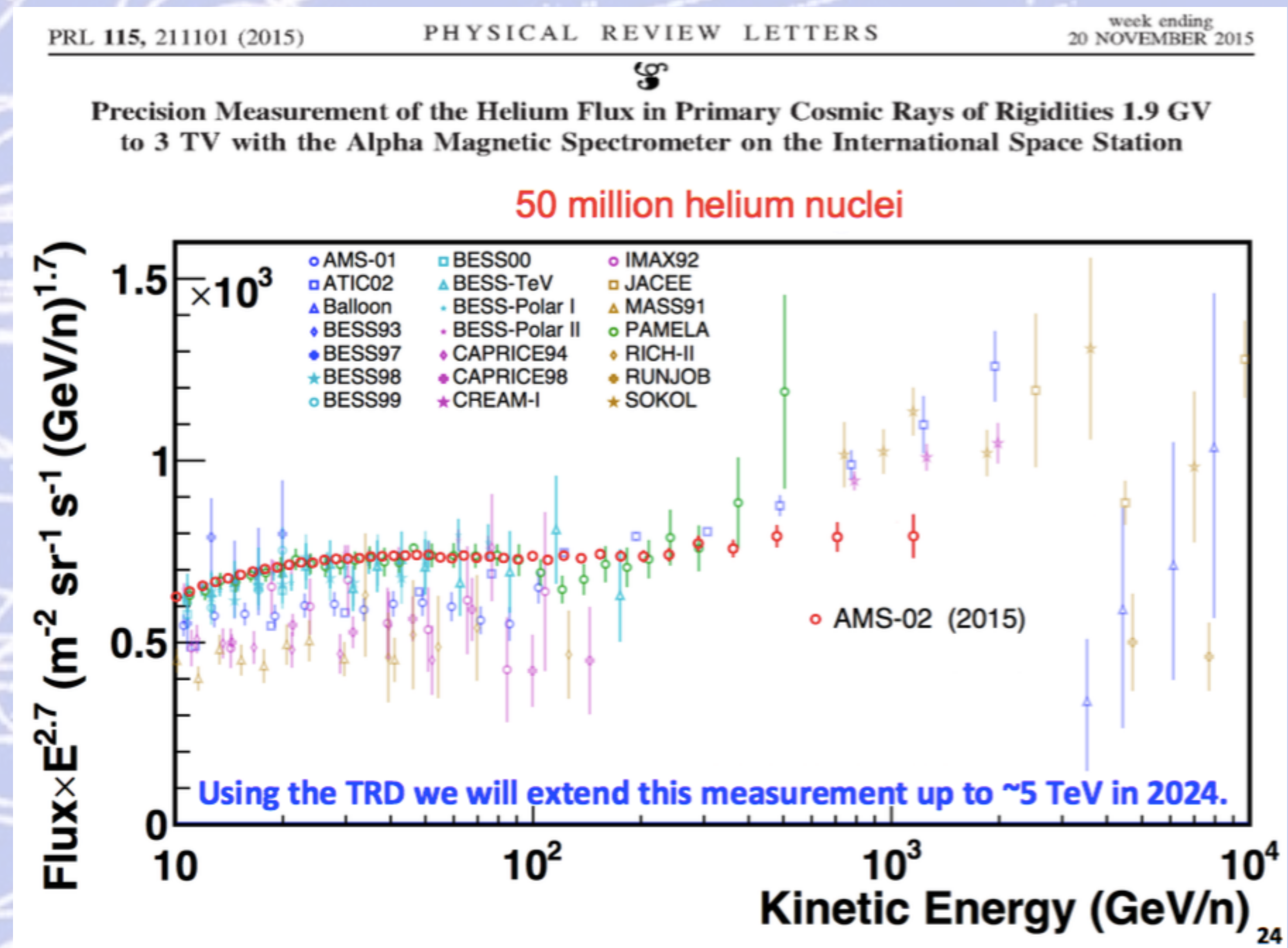


Summary
AMS results on the fluxes of elementary particles



Alcune pubblicazioni: protoni ed elio (2015)





L’Universo e’ il vero laboratorio !

I raggi cosmici sono accelerati ad energie enormemente maggiori di quelle raggiungibili da un qualsiasi dispositivo umano.

L’obiettivo principale di AMS e’ di investigare l’ignoto, ricercare fenomeni naturali che non abbiamo ancora immaginato o per i quali non abbiamo ancora sviluppato i mezzi per riprodurli e capirli.

Questa, percio', non e' la fine della storia!
Siamo solo all'inizio dei
"*Tempi Moderni*"

Grazie!

Ringraziamenti;
A. Kounine,V. Kudryavtsev,
D. Rapin, P.Salati,
S. Schael, G. Servant

Appendice 1

(I rivelatori di AMS-02)

Link utili:

Generalita':

http://math.ucr.edu/home/baez/physics/
http://home.web.cern.ch/topics
https://cds.cern.ch/collection/Videos *(cercare poi l'argomento specifico in "search")*
http://www.windows2universe.org/
http://www.cernland.net/

Astroparticelle:

http://www.astroparticelle.it/
http://www.aspera-eu.org/

Raggi Cosmici:

http://scienzagiovane.unibo.it/100RC.html
http://scienzagiovane.unibo.it/100RC/2/AlbumFoto-IIF.html
http://scienzagiovane.unibo.it/100RC/3/AlbumFoto-IIIF.html
http://www.palazzosomeda.it/Osservatorio/Raggicosmicieattivitsolare.htm

Materia Oscura:

http://www.ge.infn.it/~pesce/research/dm_tesina.pdf
http://ned.ipac.caltech.edu/level5/Bosma2/frames.html

Antimateria:

http://www.nationalgeographic.it/scienza/spazio/2012/02/16/news/nell_antimateria_il_segreto_dell_energia_oscura_-855266/
http://planet.racine.ra.it/testi/mat_osc.htm
http://scienzapertutti.lnf.infn.it/index.php?option=com_content&view=article&id=7:materia-e-antimateria&catid=5&Itemid=79
http://home.web.cern.ch/topics/antimatter/matter-antimatter-asymmetry-problem

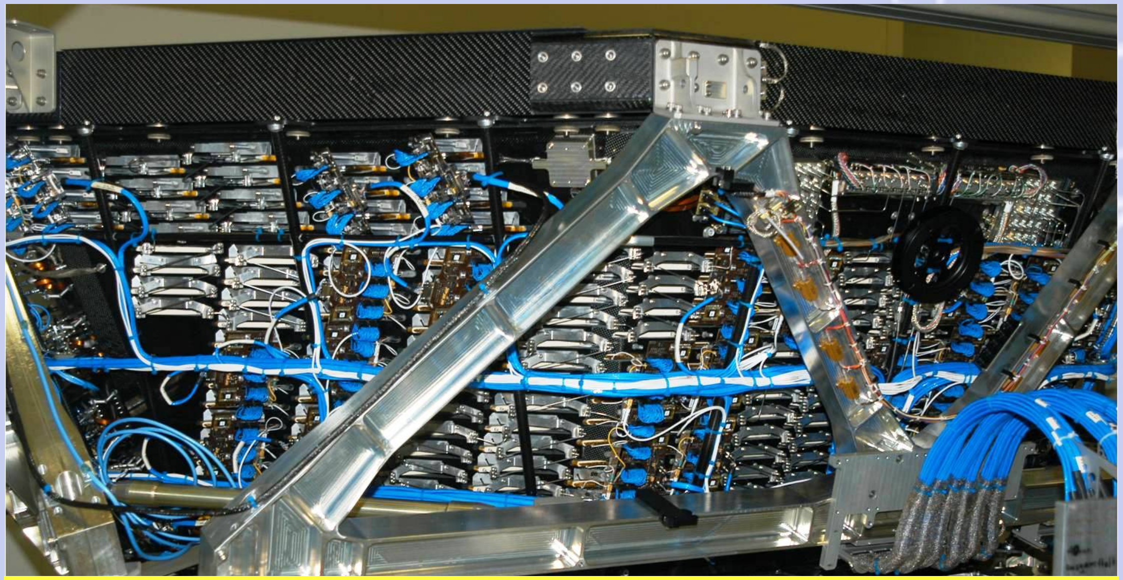
AMS e NASA:

http://www.ams02.org/ *(in "Multimedia" ci sono filmati interessanti)*
http://ams.nasa.gov/
http://www.ustream.tv/NASAHDTV (in "Videos" sono disponibili diversi filmati)

Lavori didattici:

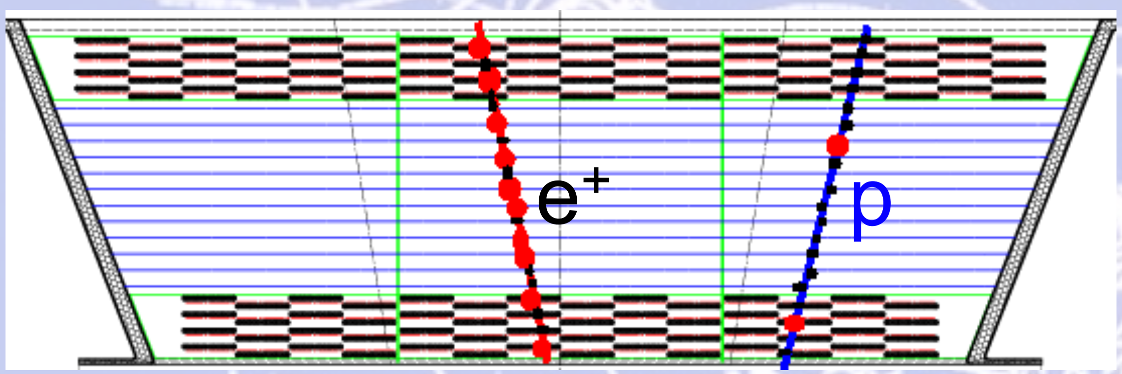
http://try.iprase.tn.it/old/in05net/upload/doc/libri/U1011t3n729_Raggi_cosmici.pdf
http://www.liceogioberti.it/didattica/prog_EEE_articoloCeresole.pdf
http://eee.centrofermi.it/component/k2/item/download/1_80cbadb159b503626a30e04b169f2372
http://appunti.studentville.it/appunti/tesine-6/tesina_antimateria_realta_o_fantasia-3391.htm (scaricare il file)

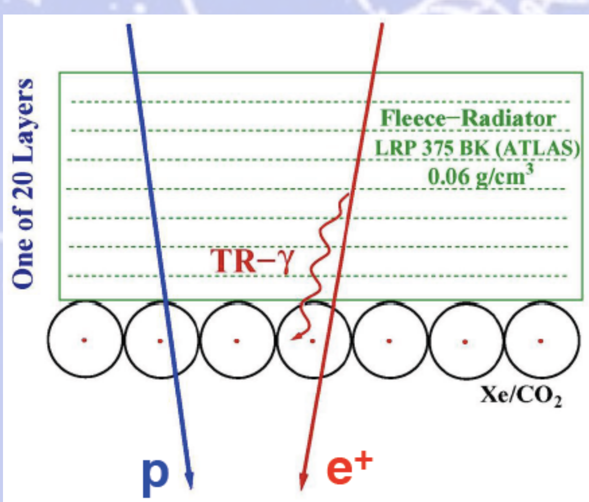
Transition Radiation Detector (TRD)



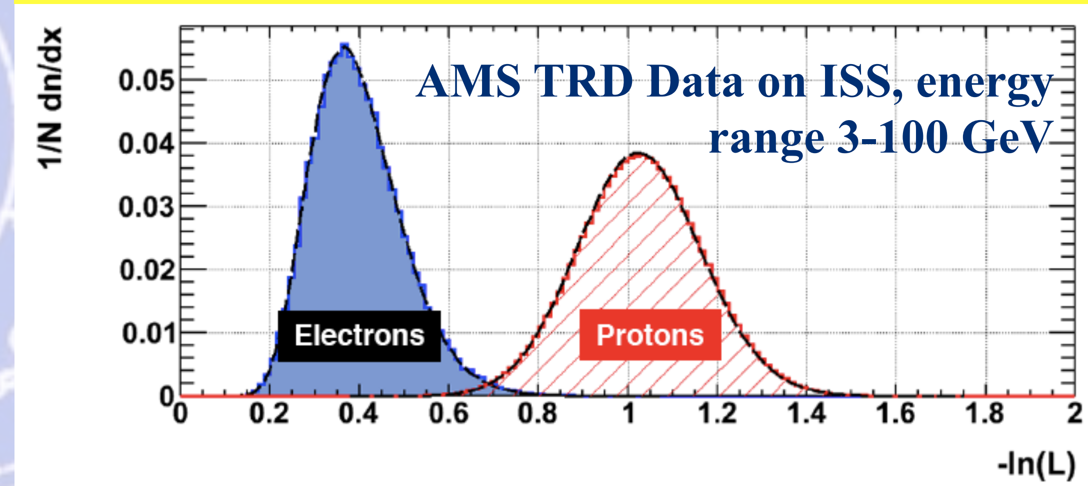
20 layers assembled in octagonal structure;
328 modules of fleece and straw tubes;
Gas mixture: 80% Xe – 20% CO_2;

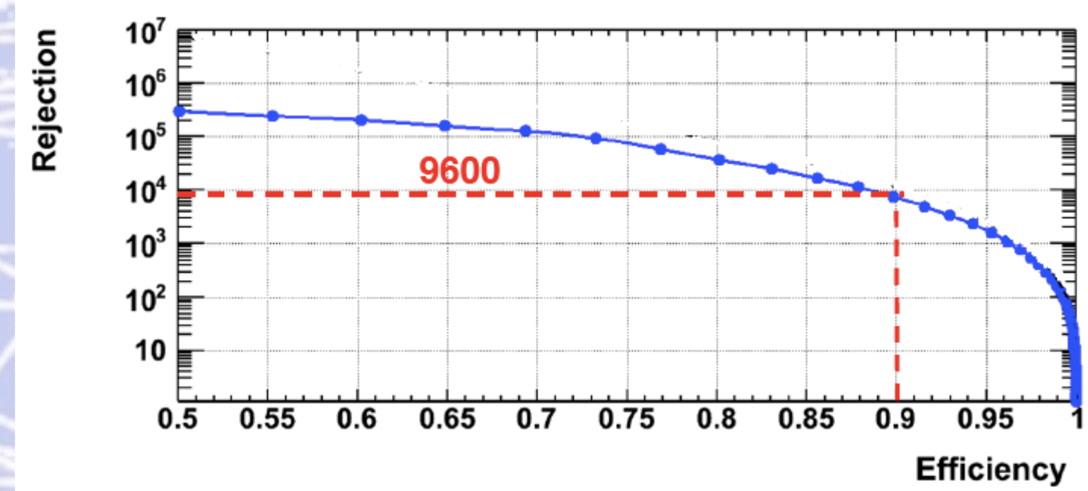
Leakrate of 5 µg/s, caused by CO_2 diffusion, corresponds to a lifetime ~20 years in Space

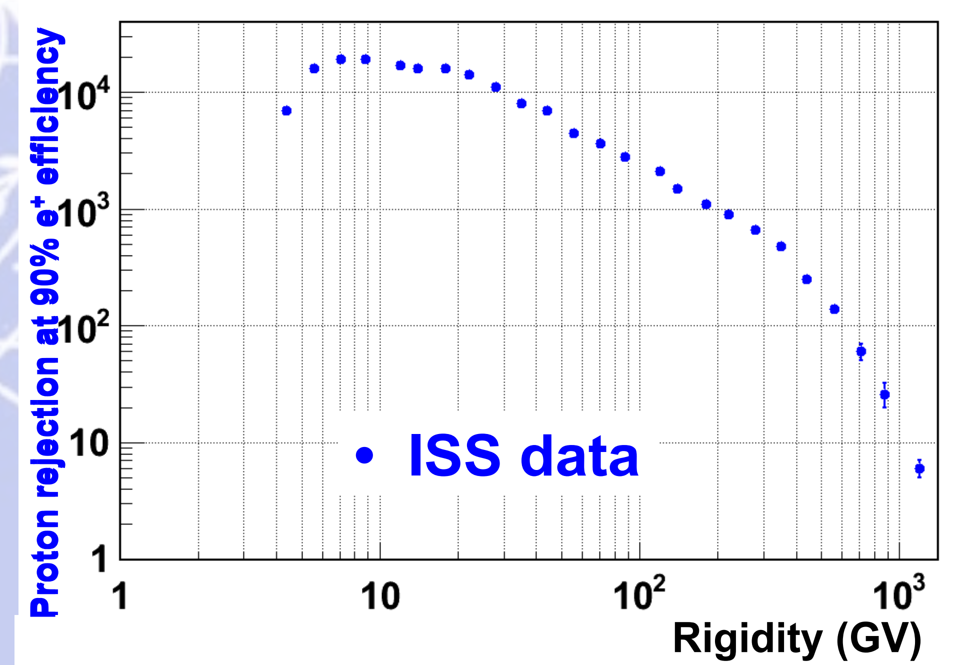




identifies e± by transition radiation and Nuclei by dE/dX

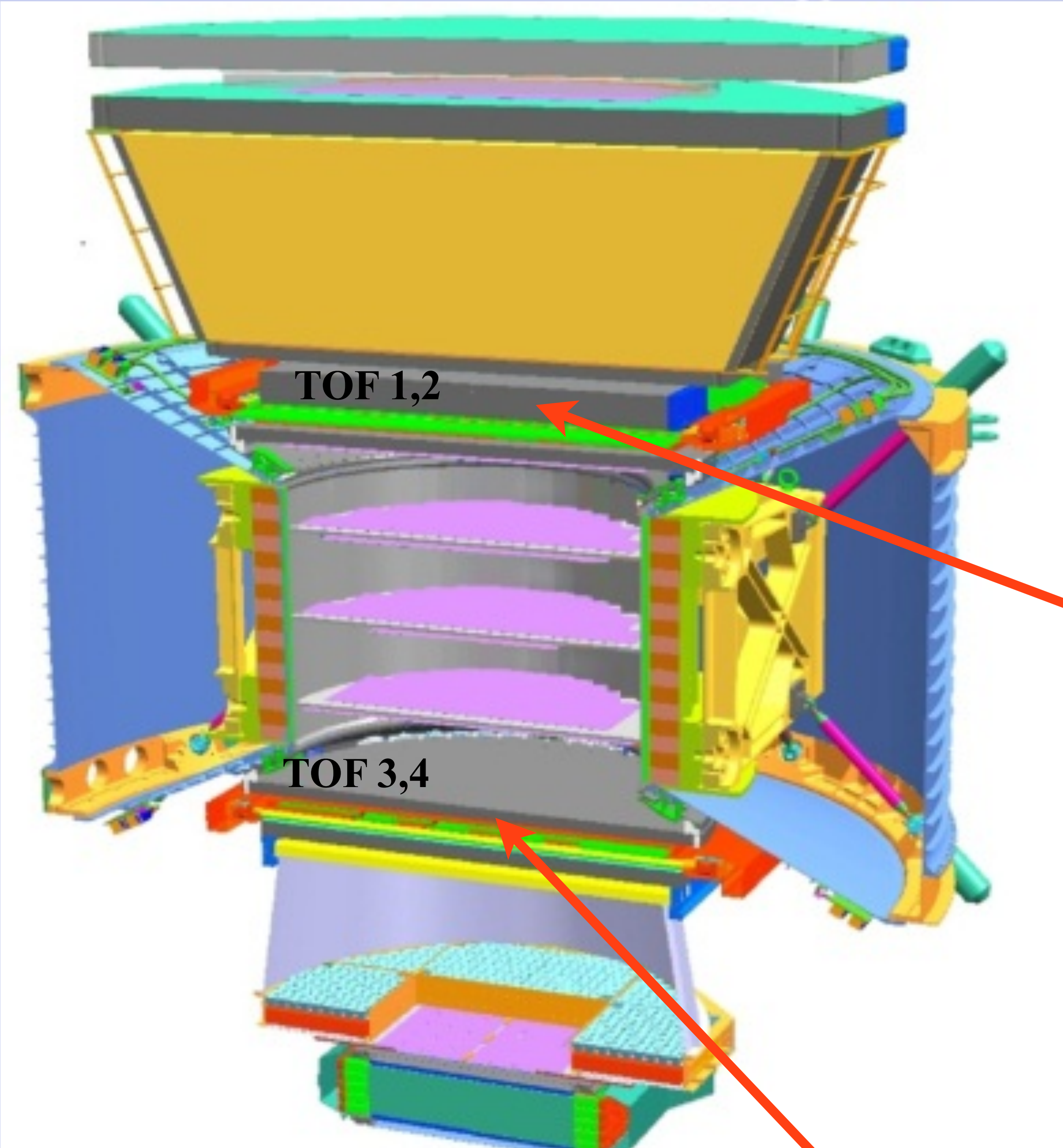


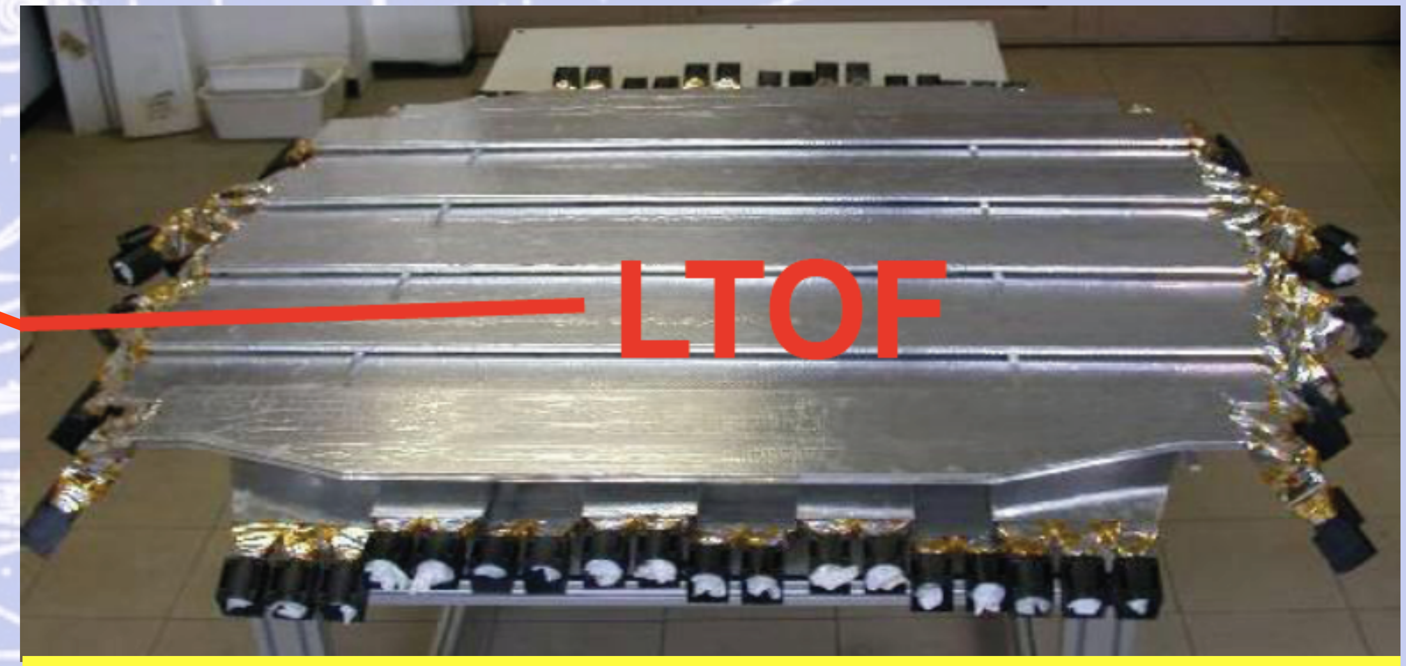




Time of Flight (TOF)

Measures Velocity and Charge of particles





2x2 planes + total of 34 scintillator paddles (seen by 2 (or 3) PMTs on each side);

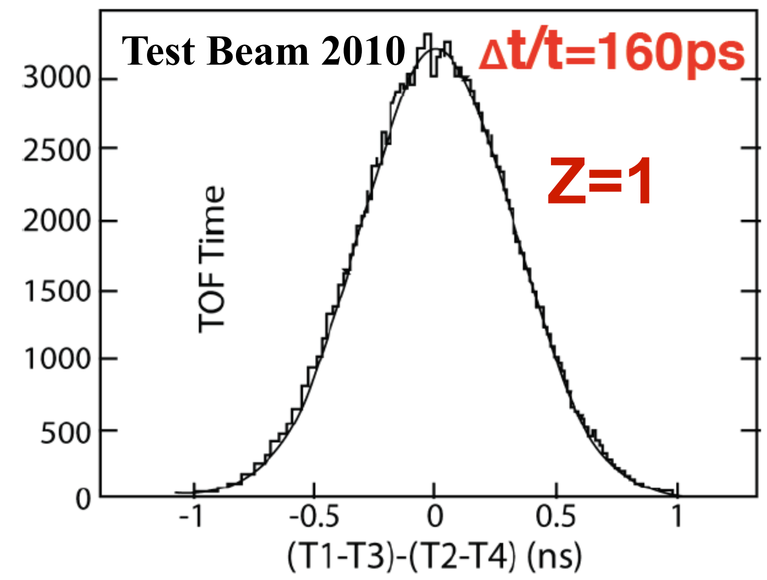
Measures the time of relativistic protons to 160 picoseconds

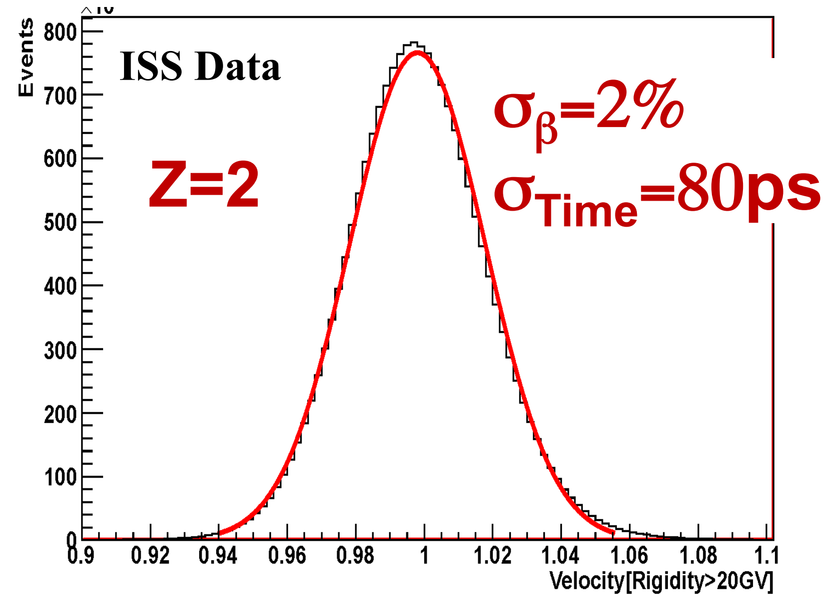
Provides trigger for charged particles

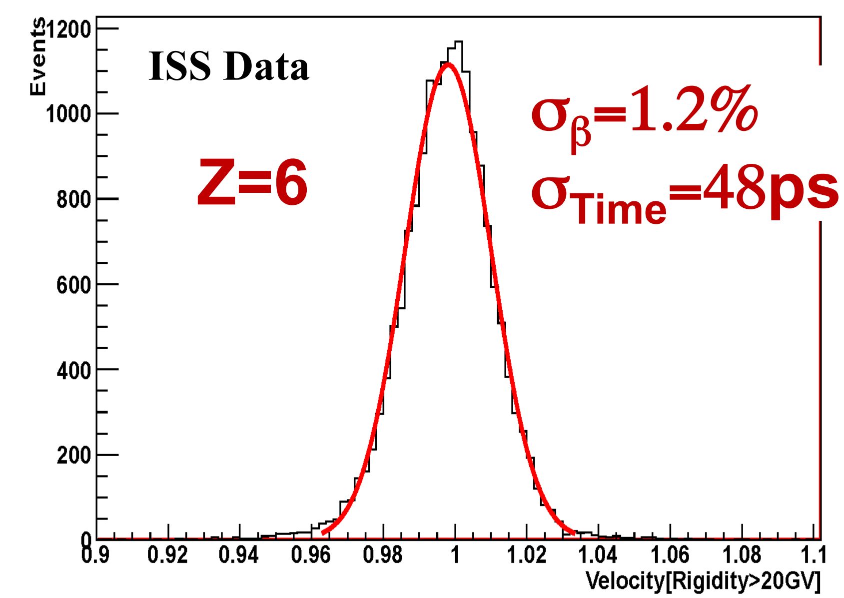
Trigger time is synchronized to UTC time to 1µs

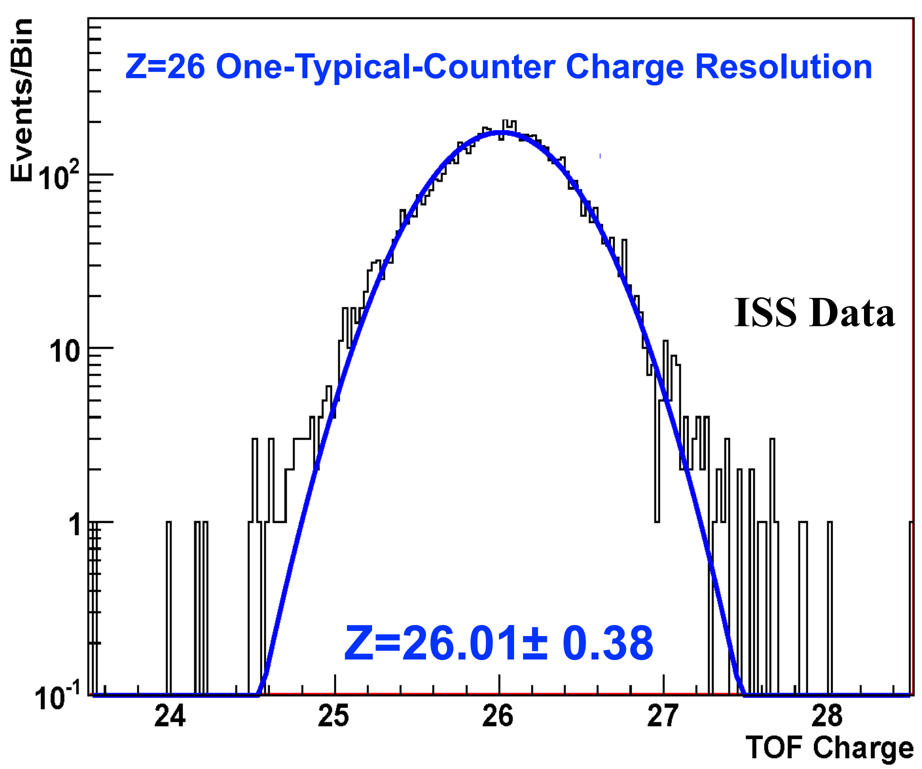
Time of Flight (TOF):

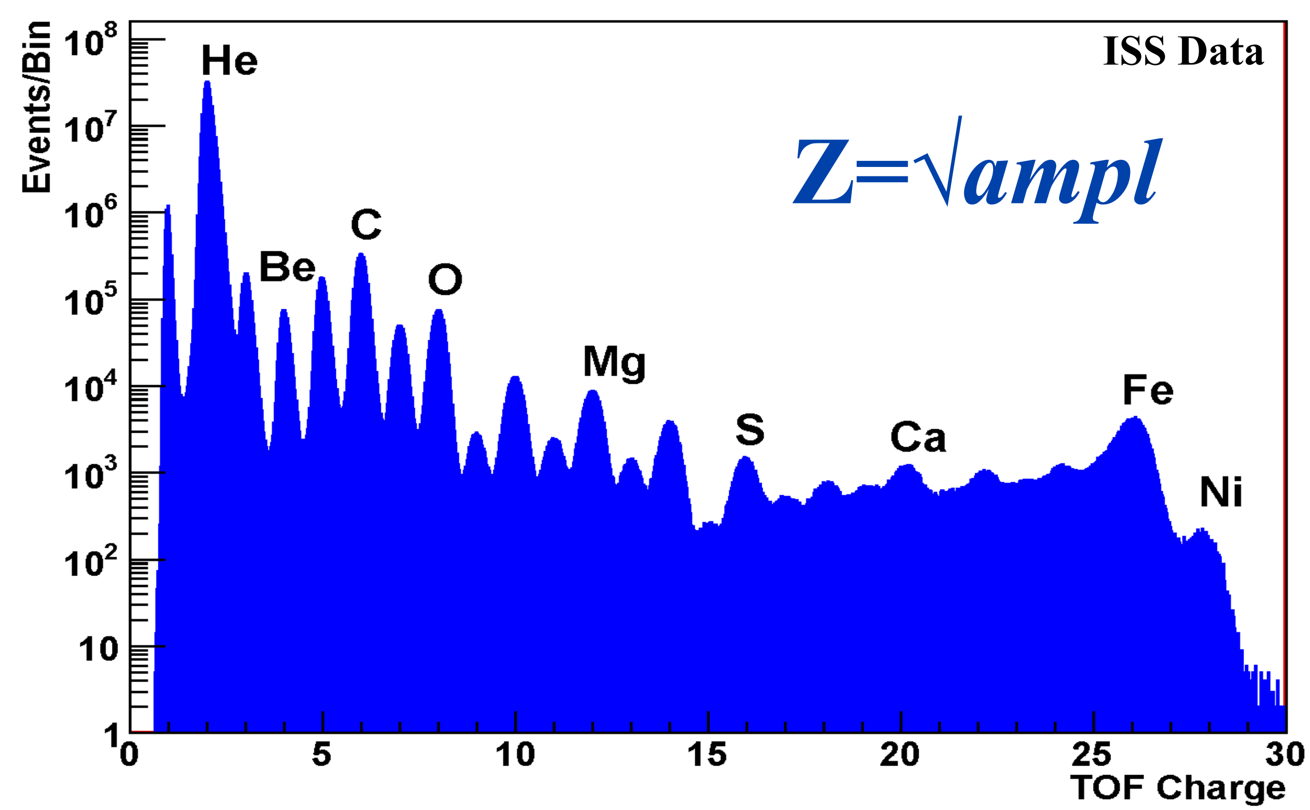
Measures Velocity and Charge of particles



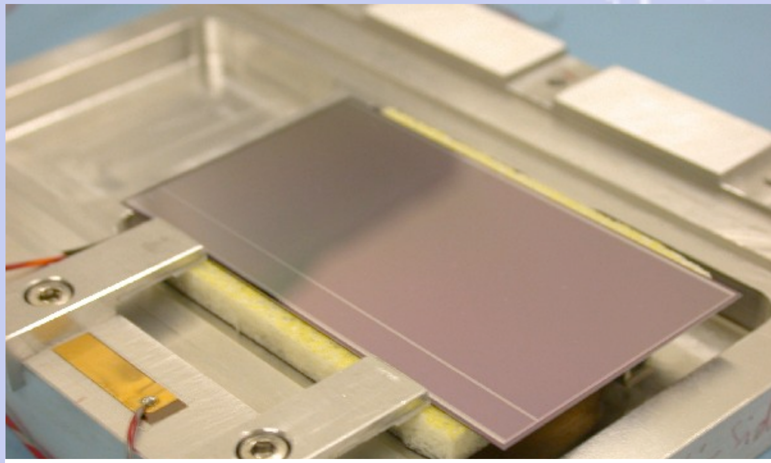


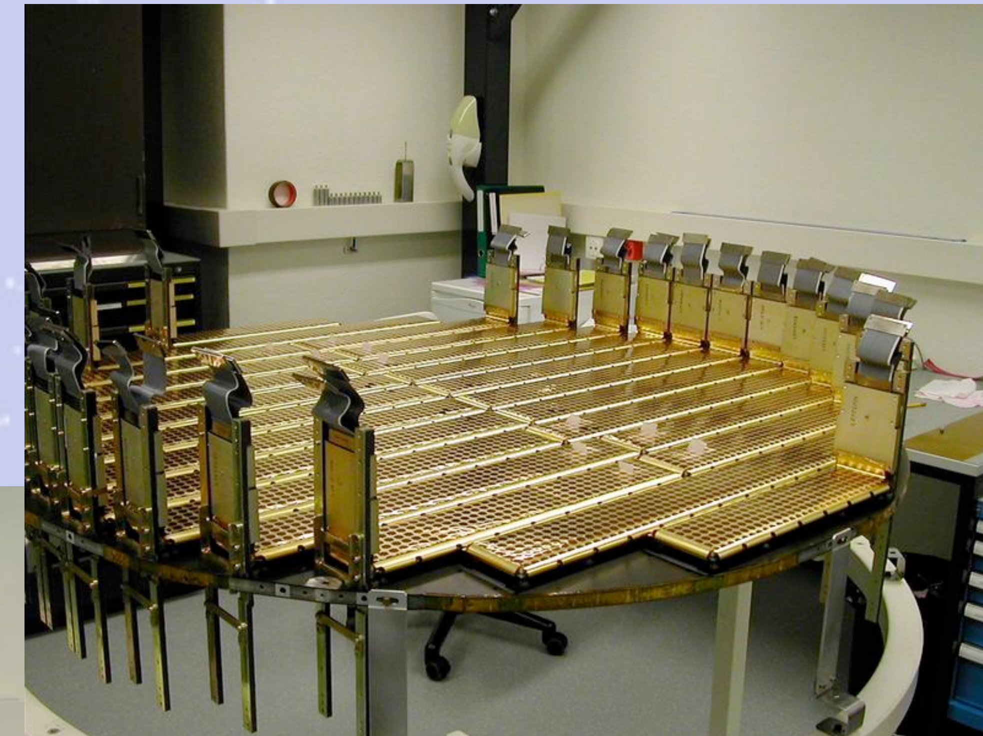


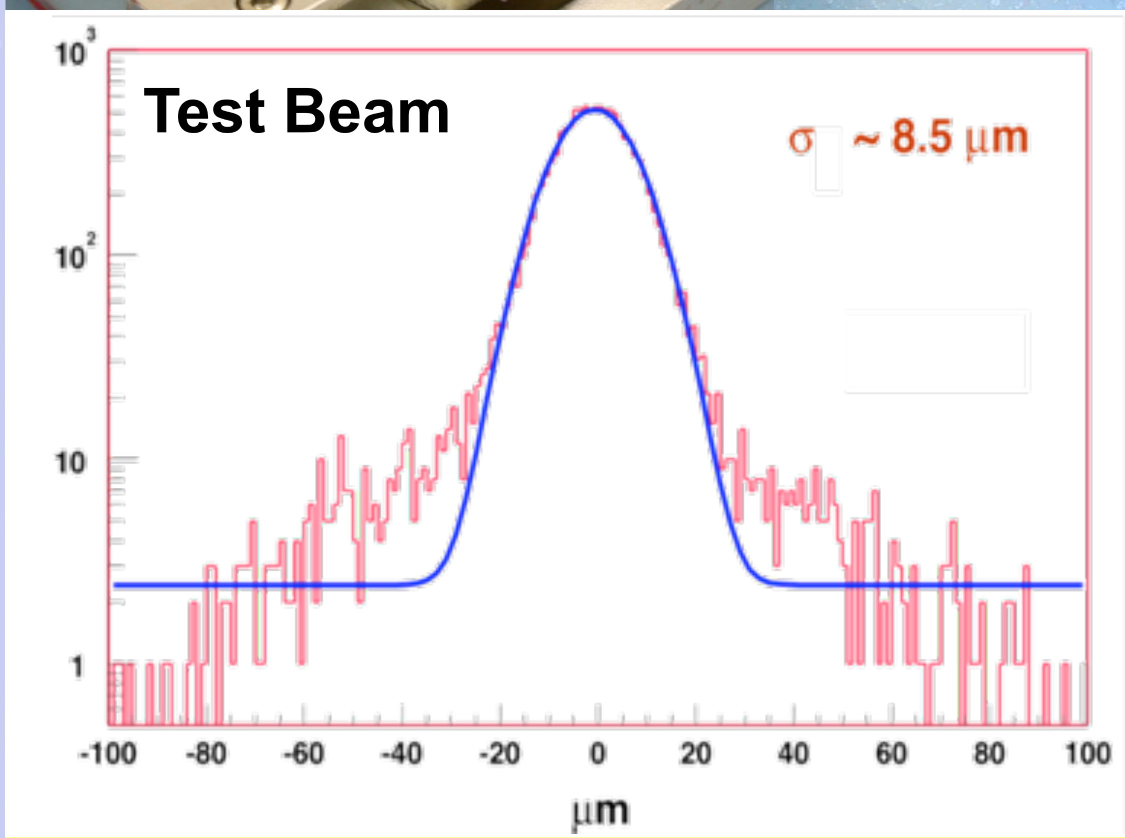


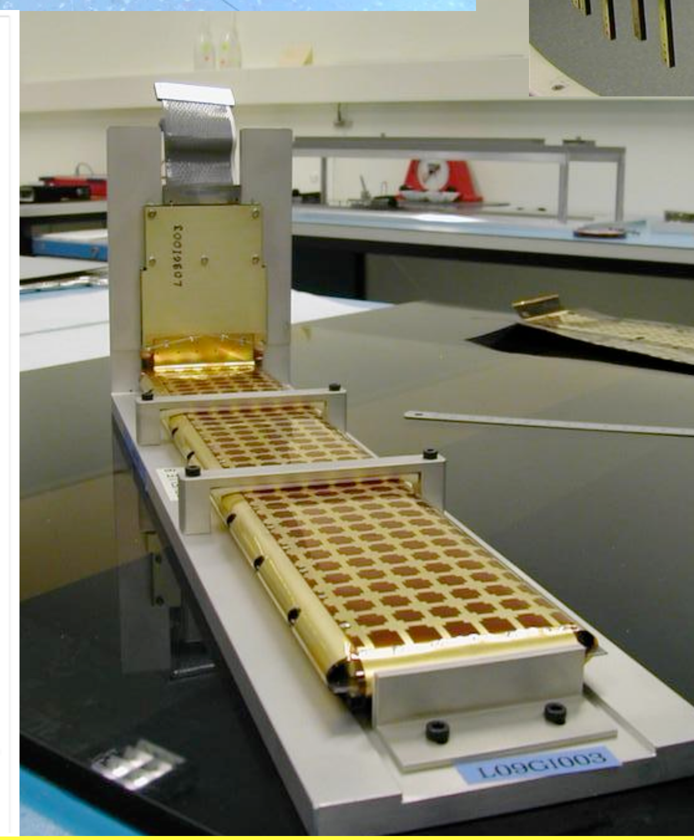


Tracker









9 layers of double sided silicon sensors (detector material ~ 0.04 X_0)
6.6m² → 192 Ladders → 196k channels → 192 Watts dissipated

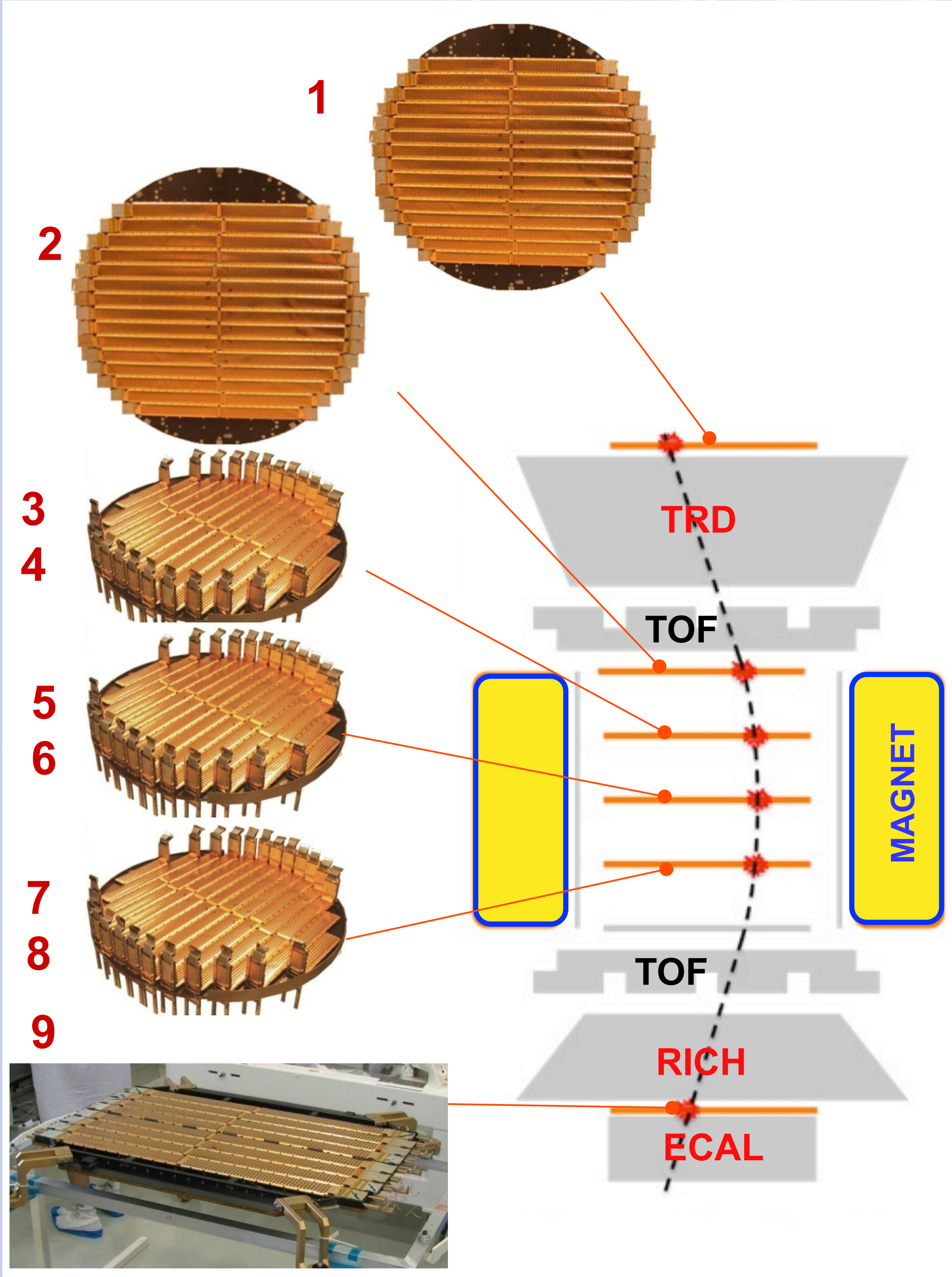
Spatial resolution:
- **(σ) ~8µm (bending plane)**
- **(σ) ~30µm (non bending plane)**

Momentum resolution ~10% at 10 GV

Wide temperature range (-20/+40 survival, -10/+25 oper.)

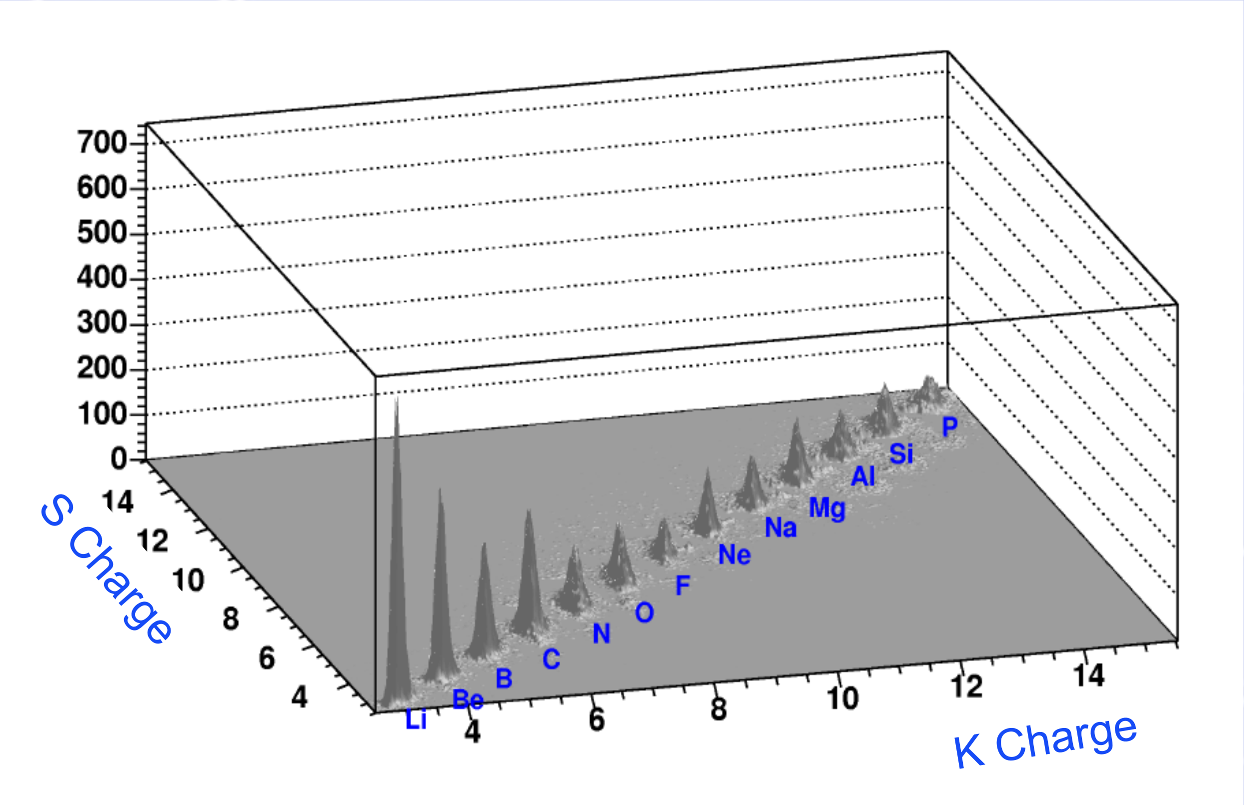
High dynamic range front end for charge measurement

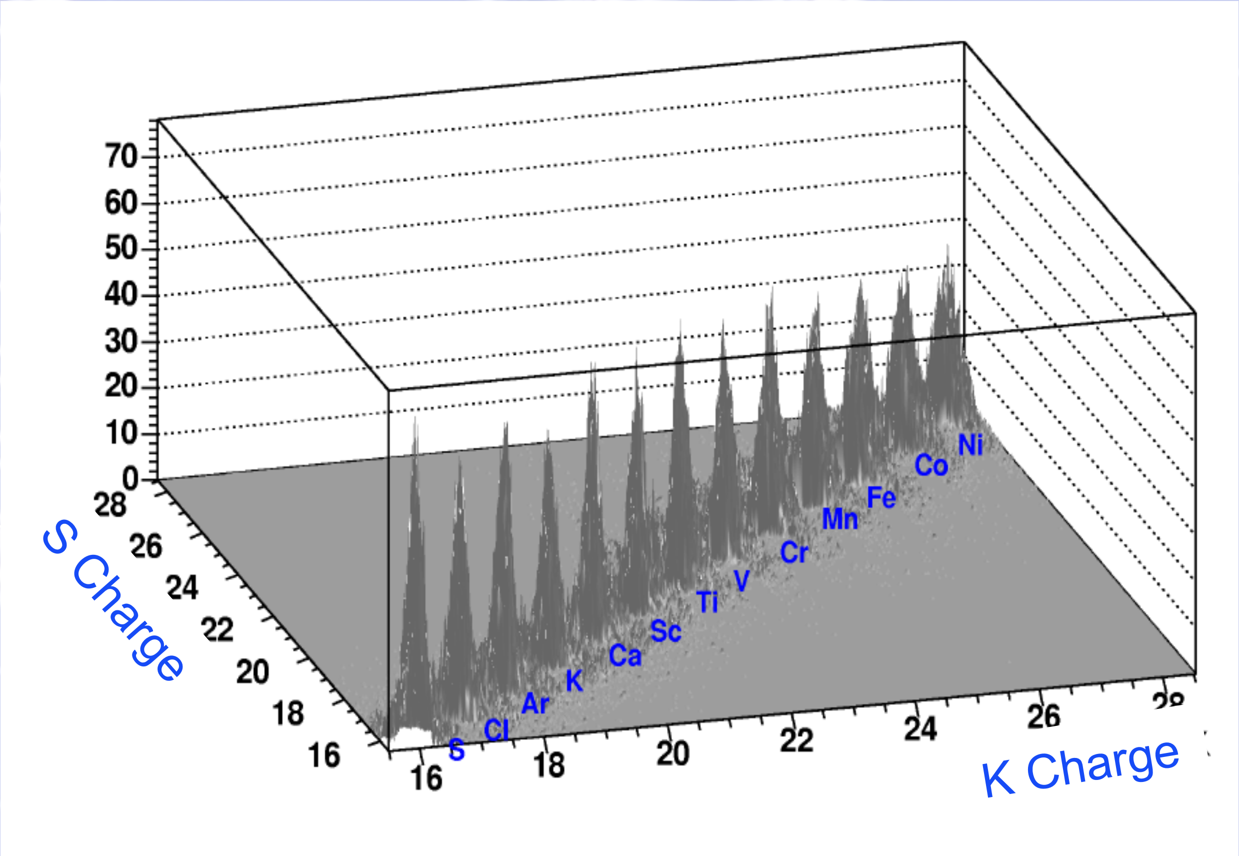
Tracker



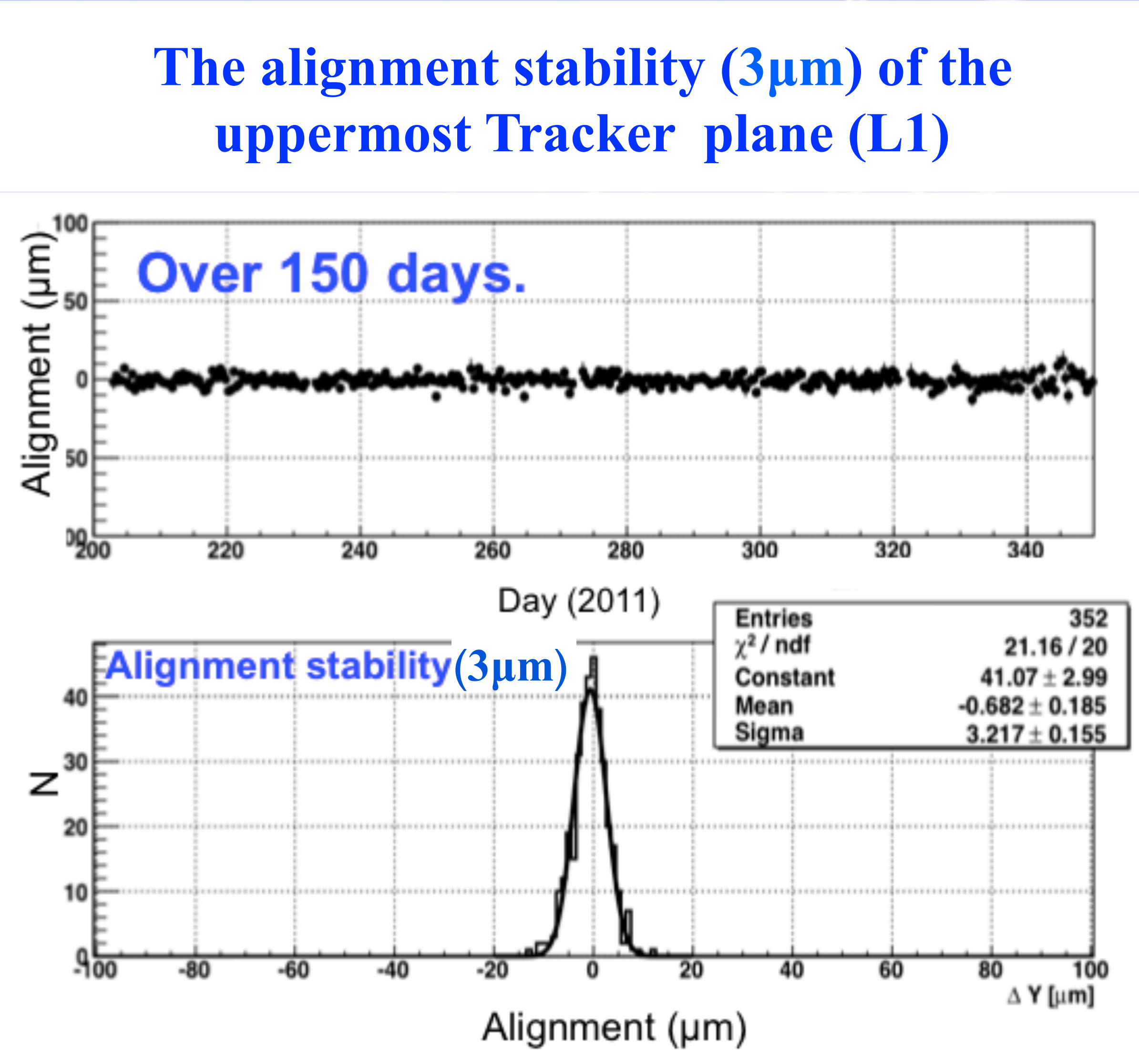
The particle trajectory is measured on several points (9) by its intersection with silicon microstrips detector layers.

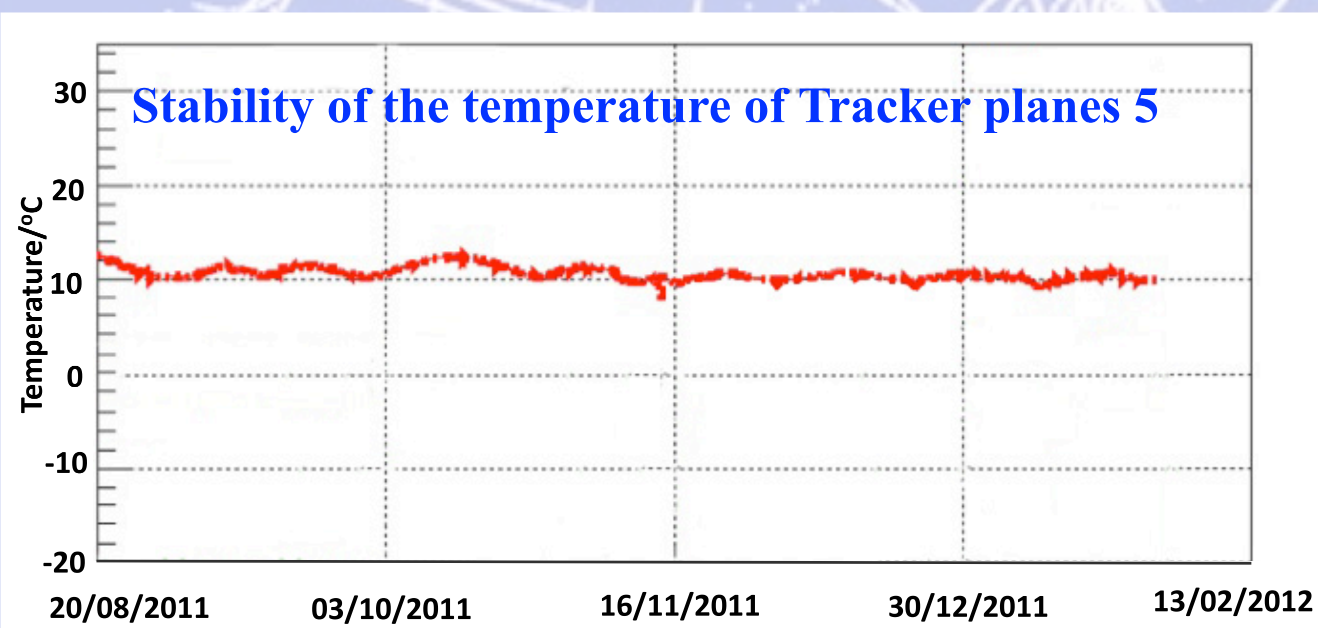
Nuclei identification

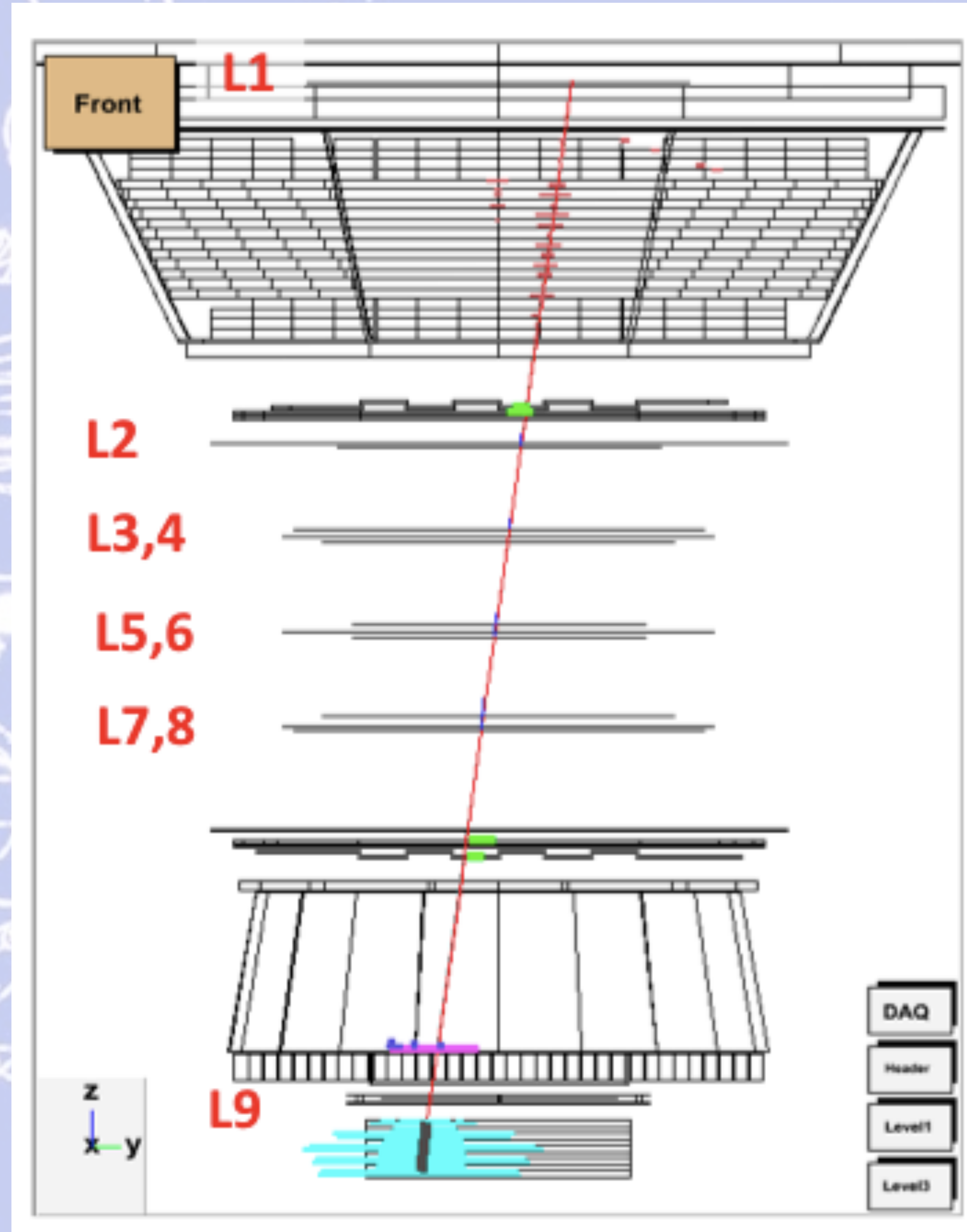


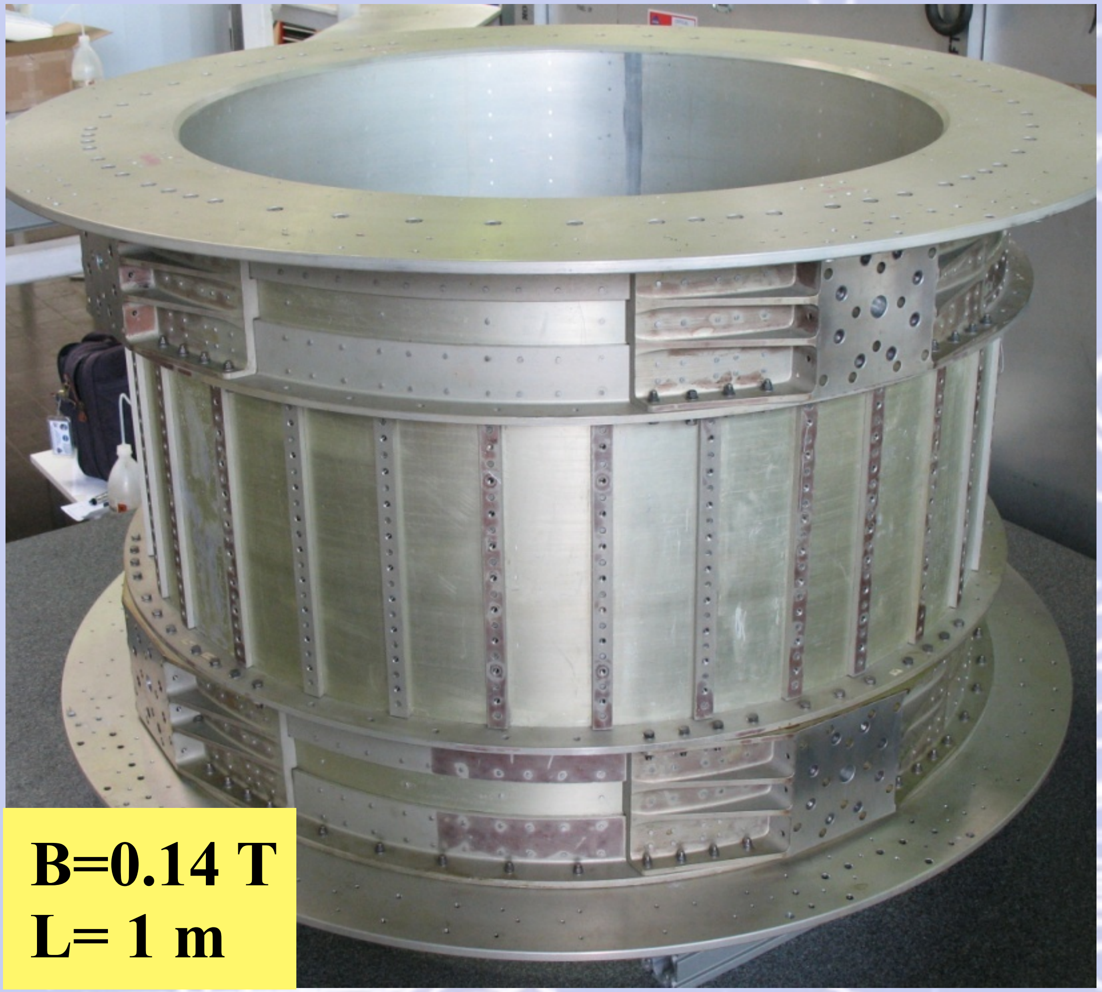


Tracker Performance on ISS





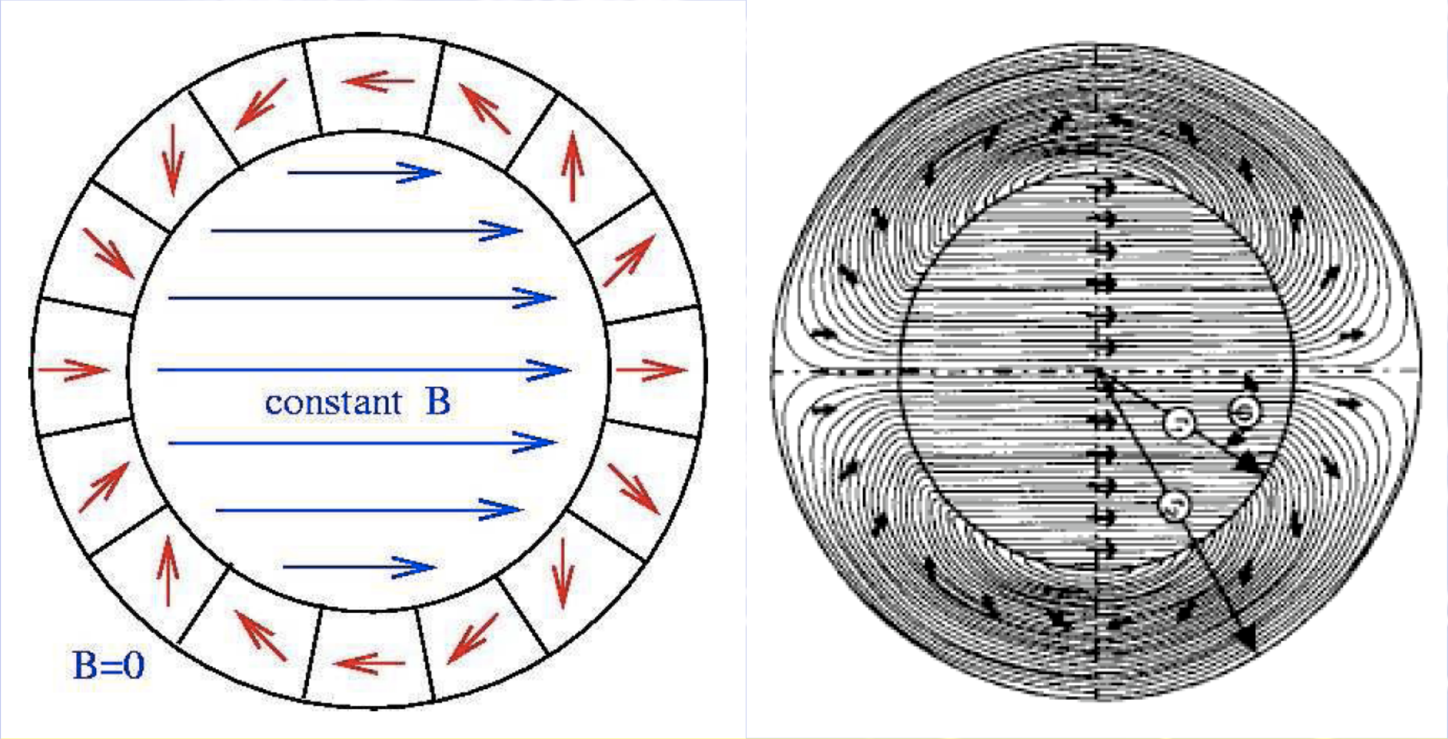




The AMS-02 permanent Magnet

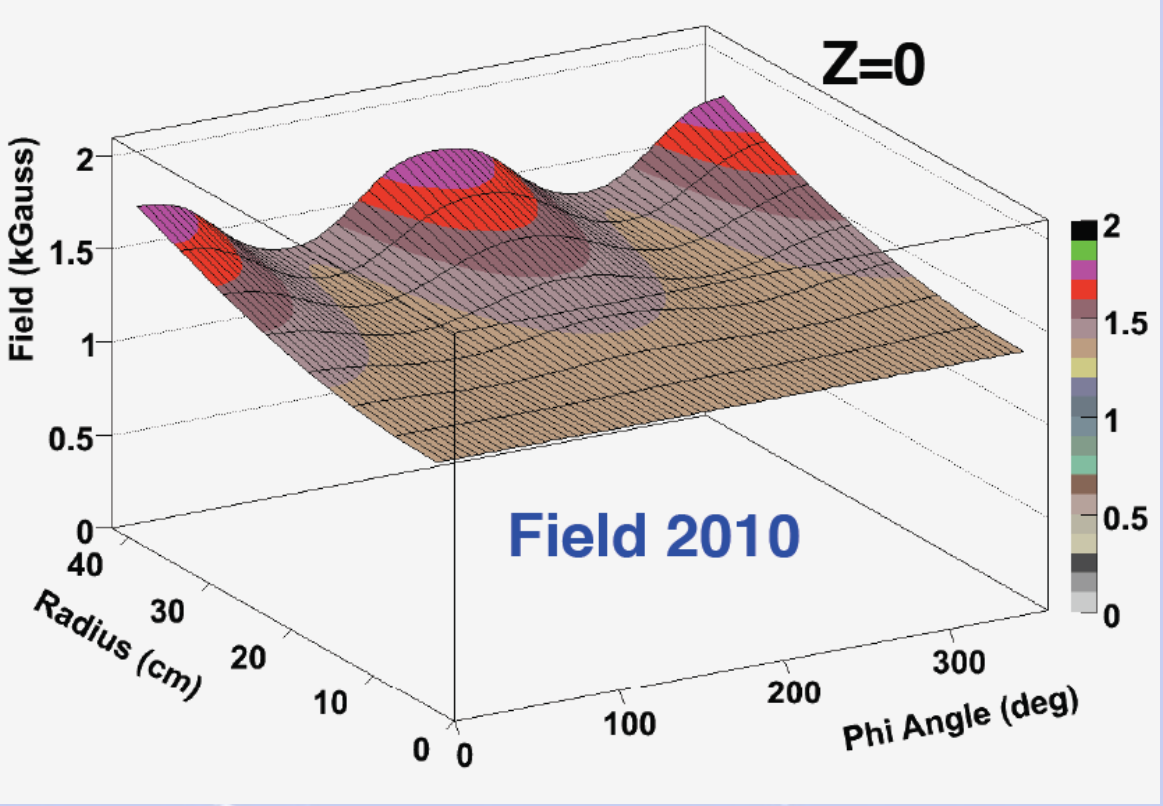
Torques are forbitten in space so the total magnetic torque of the AMS-02 magnet must be zero!

B=0.14 T
L= 1 m



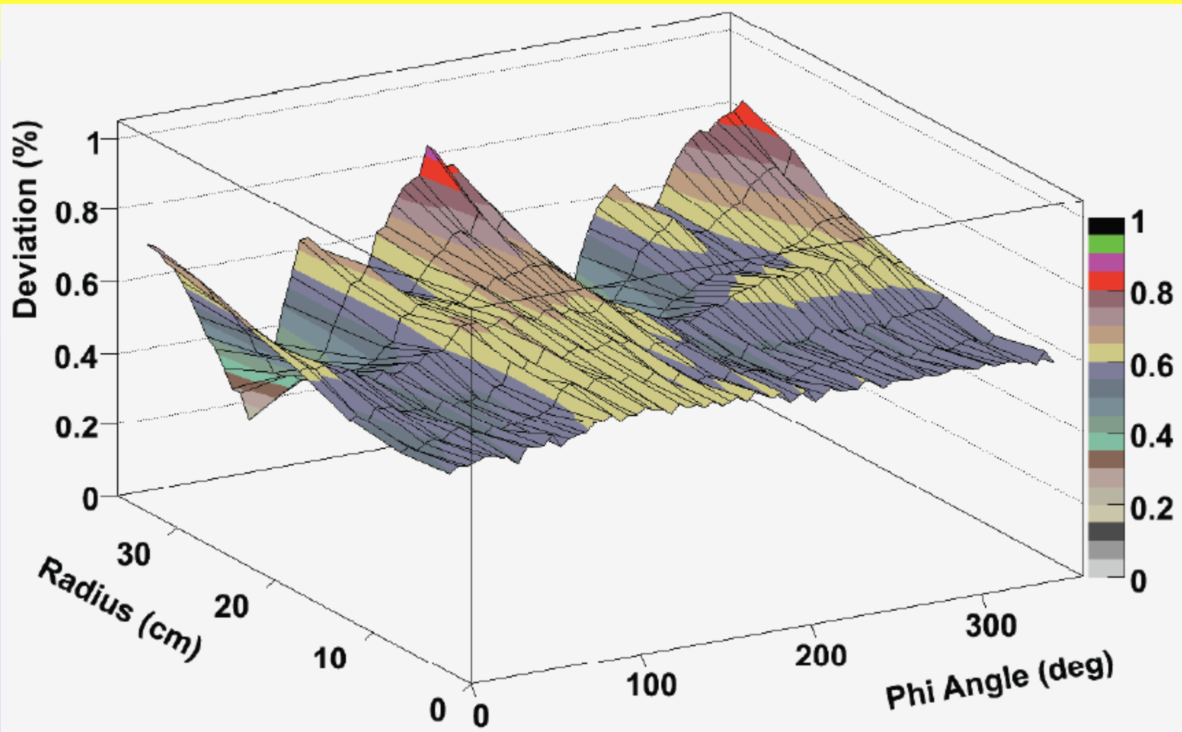
Magnetic field distribution at a cross-section of the centre of the magnet

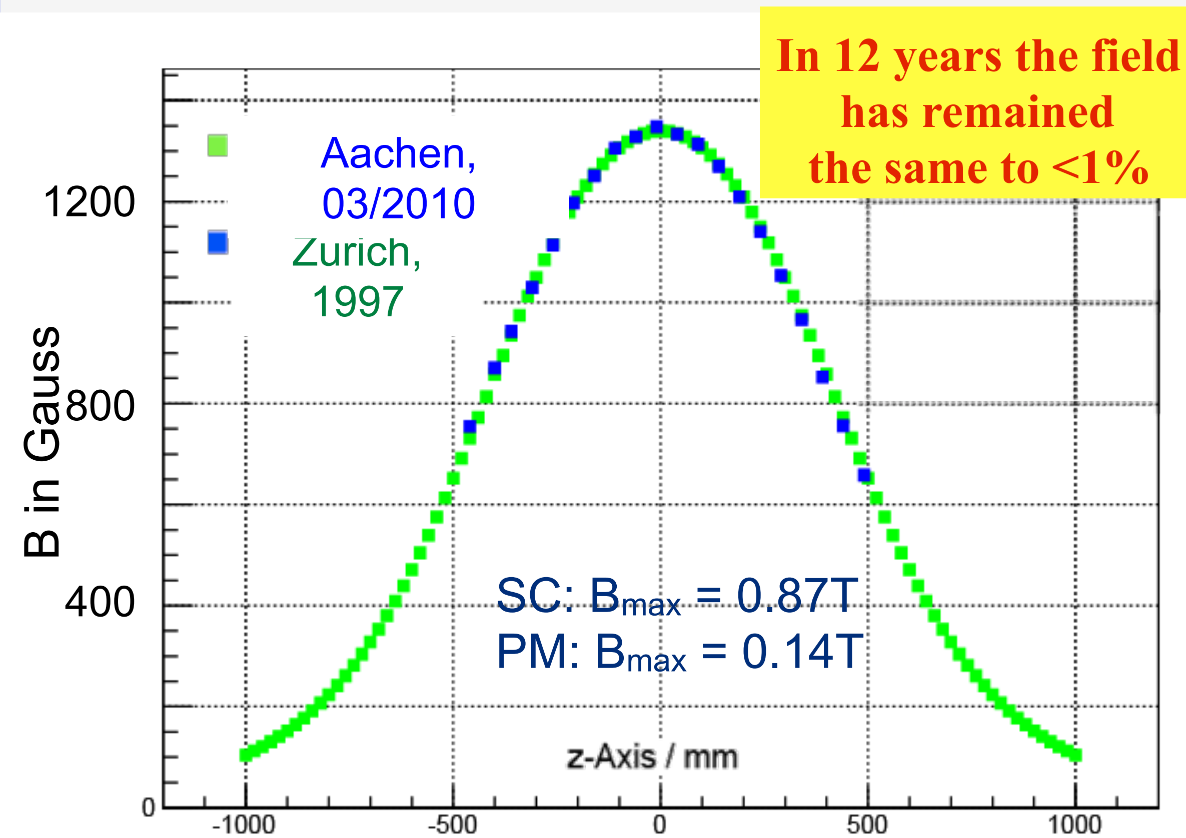
The detailed 3D field map (120k locations)



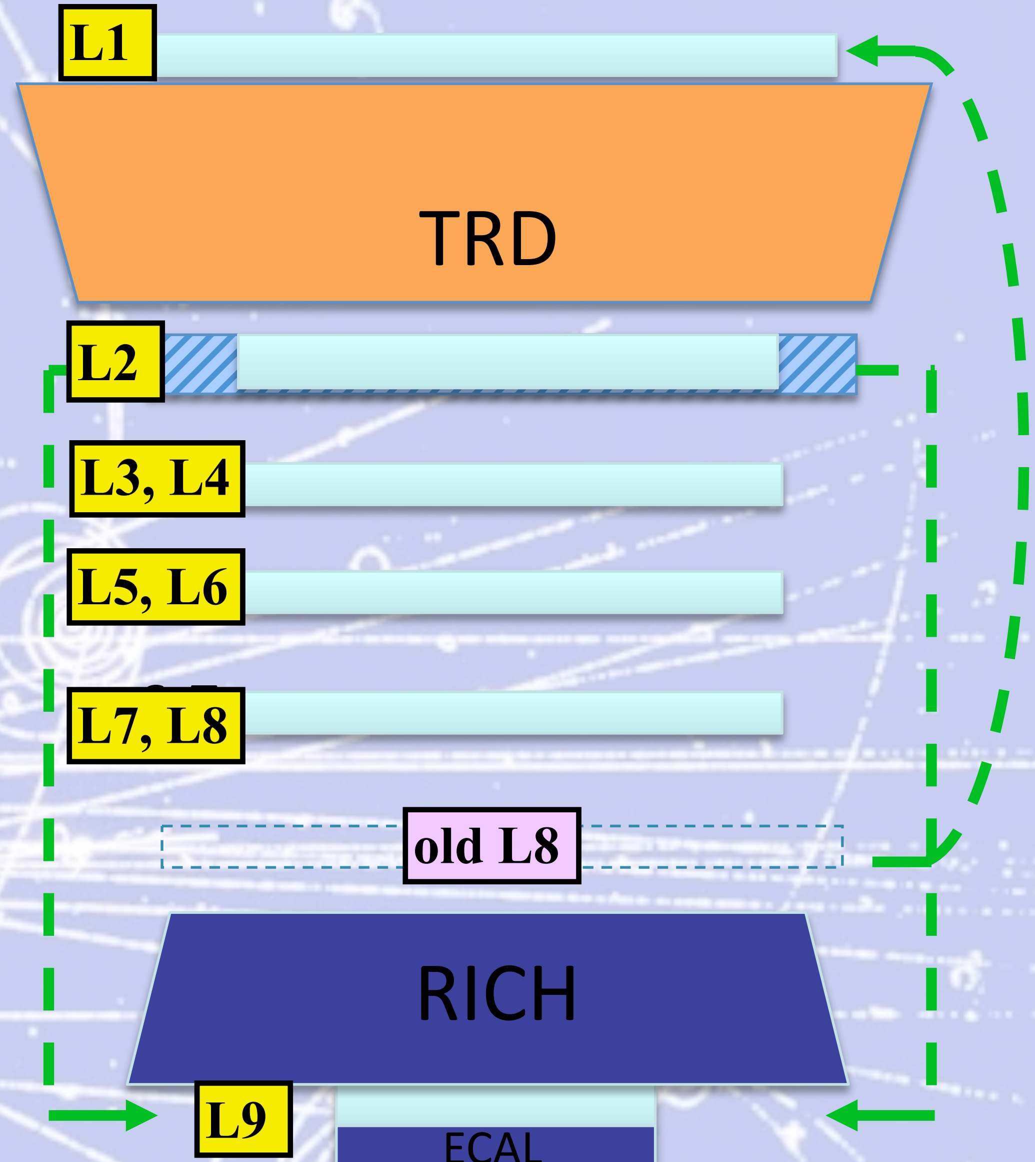
The AMS-02 Spectrometer modifications

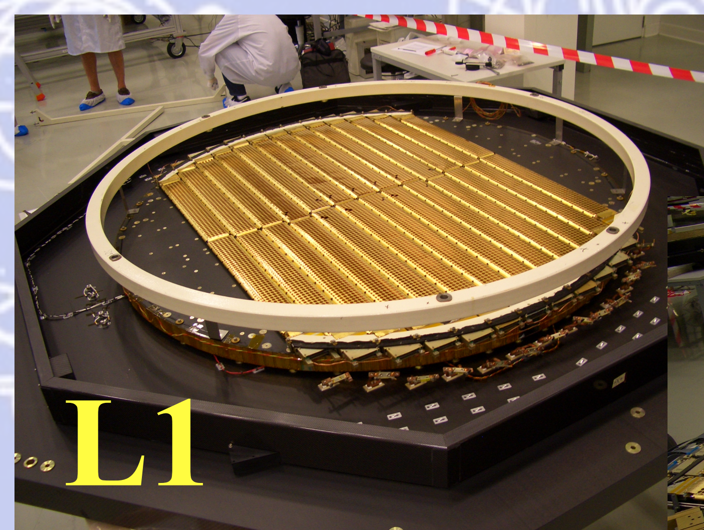
Deviation from 1997 measurements

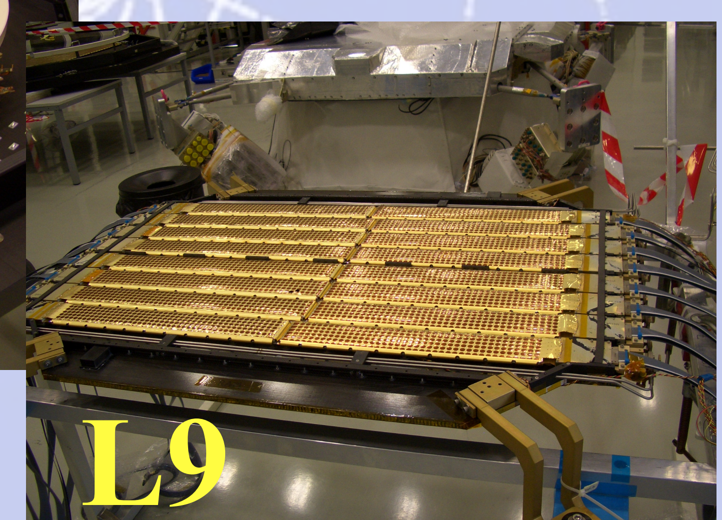




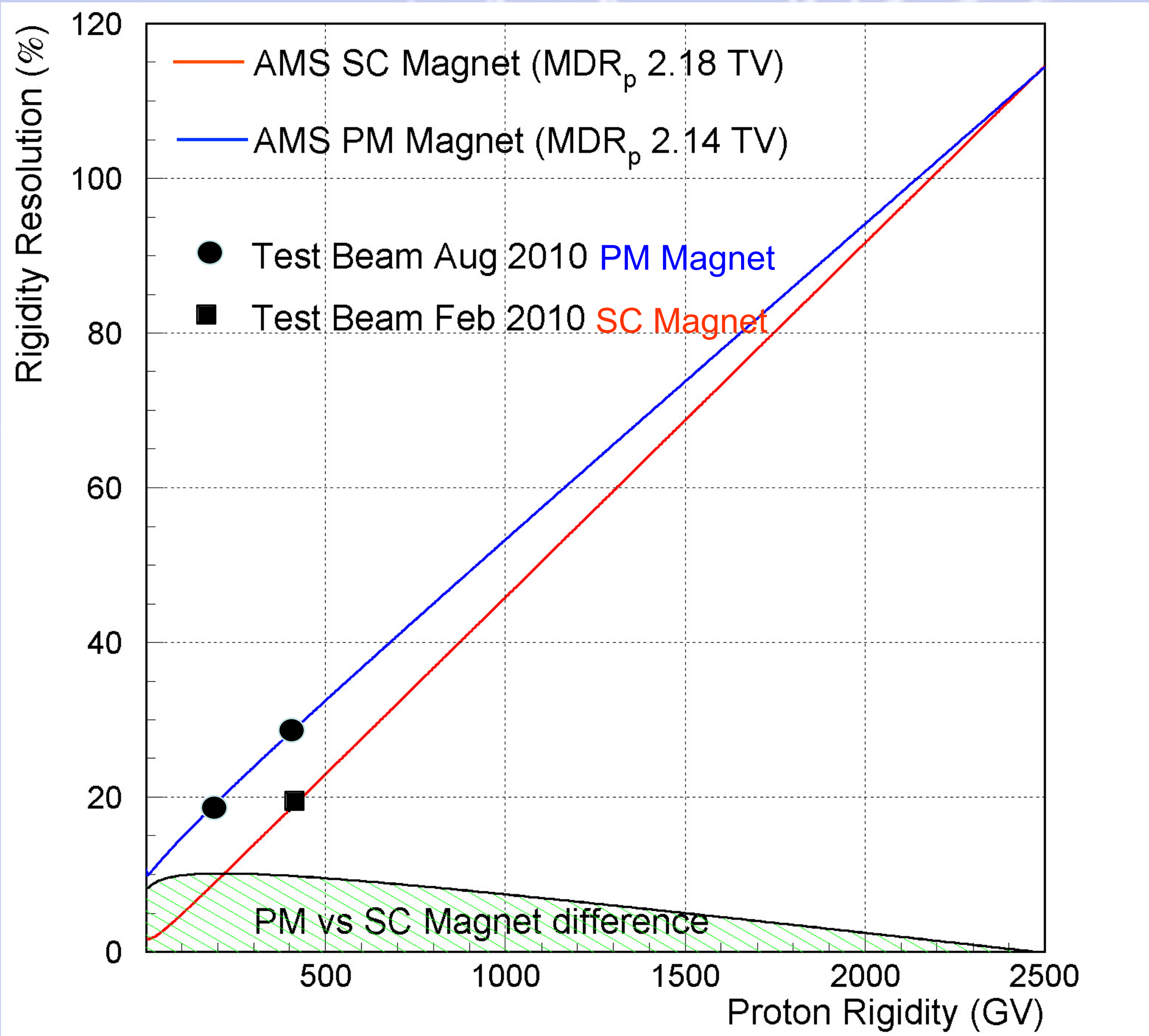
In 12 years the field has remained the same to <1%





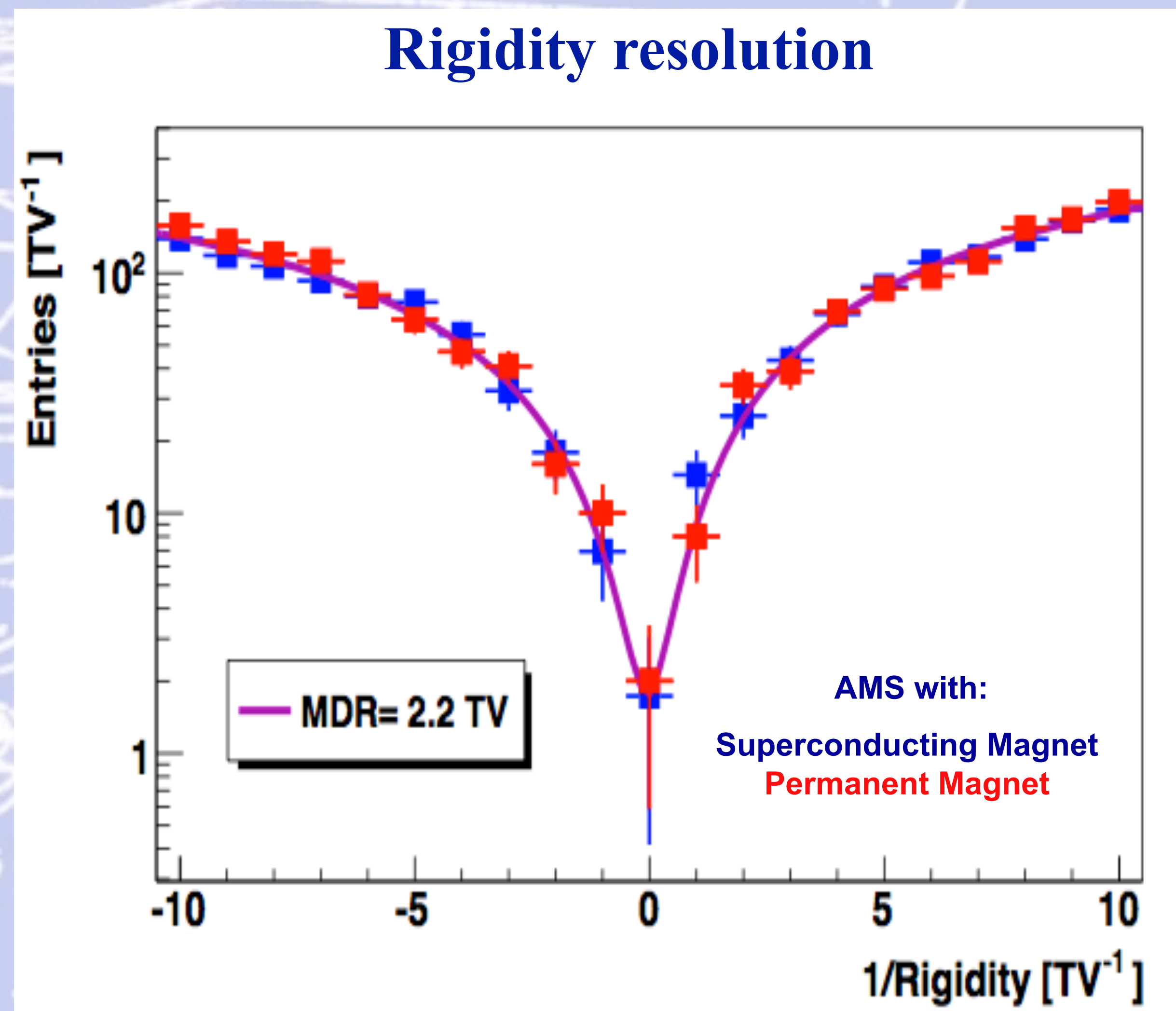


The AMS-02 Spectrometer performance



- **For helium nuclei, the MDR(*) for the permanent magnet is 3.75 TV.**
- **Alignment will be done with 10'000 CR tracks per minute in orbit.**

(*) Max detectable rigidity (R=pc/Ze)

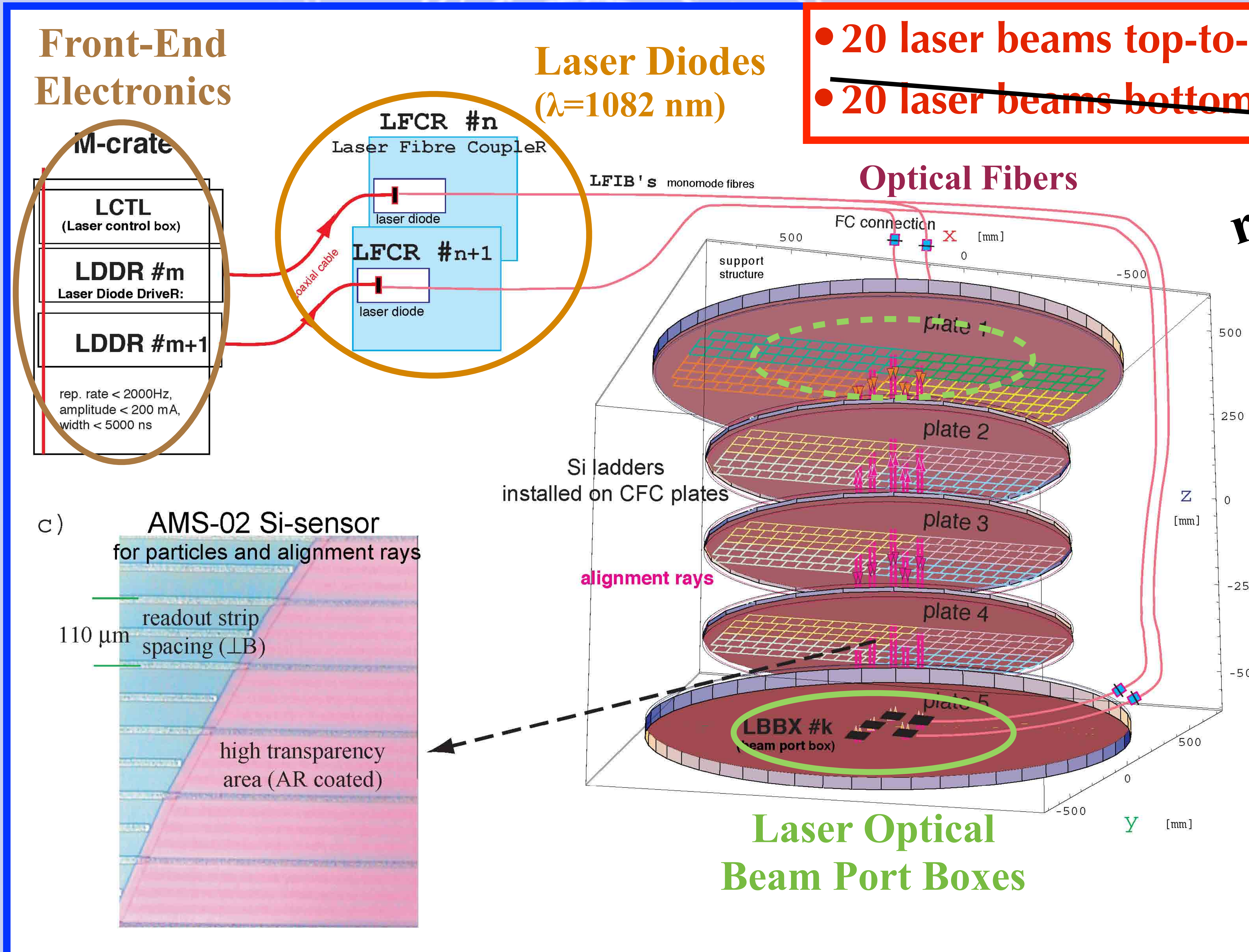


With 9 tracker planes in the new configuration, the rigidity resolution of AMS with the permanent magnet is equal (within 10%) to that of the superconducting magnet.

The AMS-02 Tracker Alignment System Layout

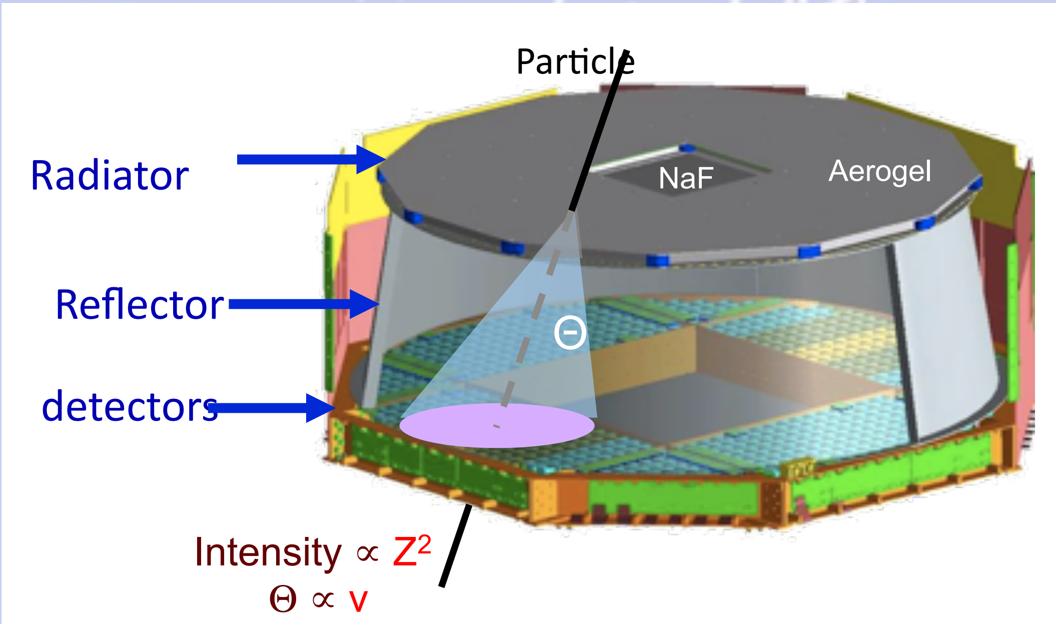
- 20 laser beams top-to-bottom
- ~~20 laser beams bottom-to-top~~

removed!

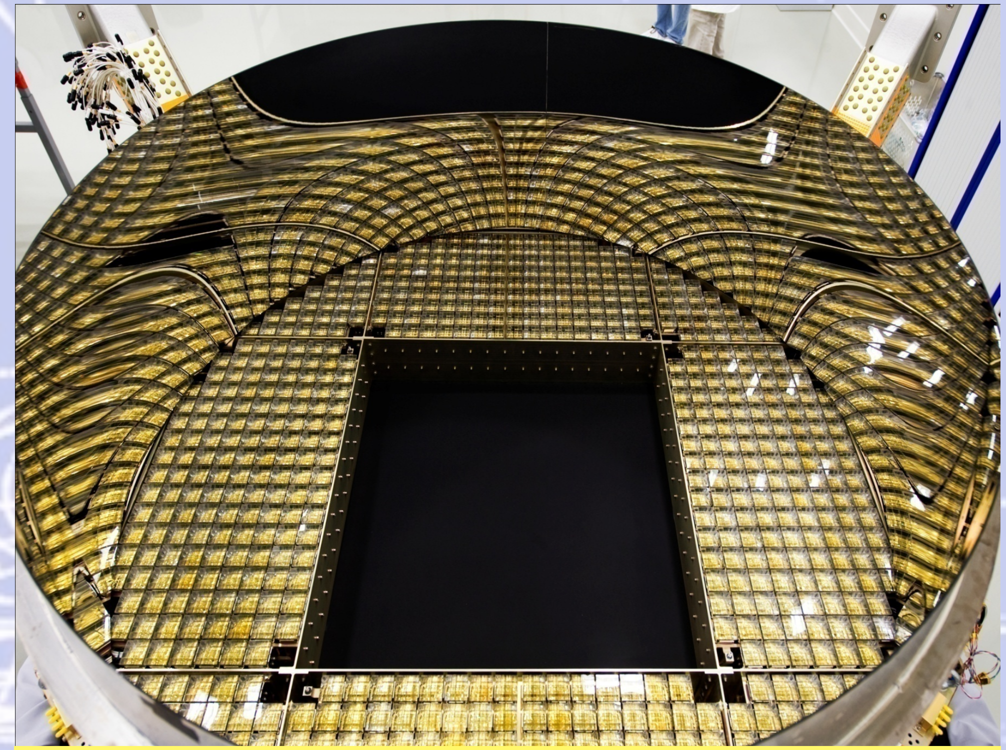


Ring Imaging Cherenkov (RICH)

identify nuclei and their energy



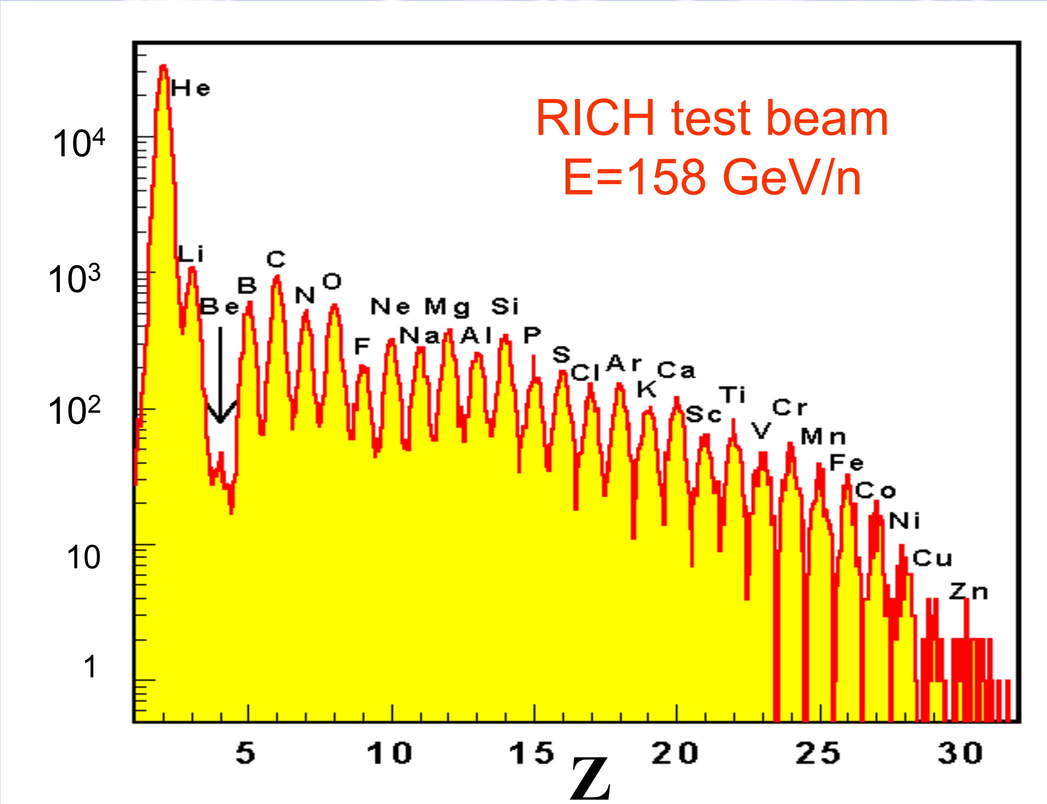
3cm silica Aerogel(n=1.05) +NaF (n=1.33) radiator;



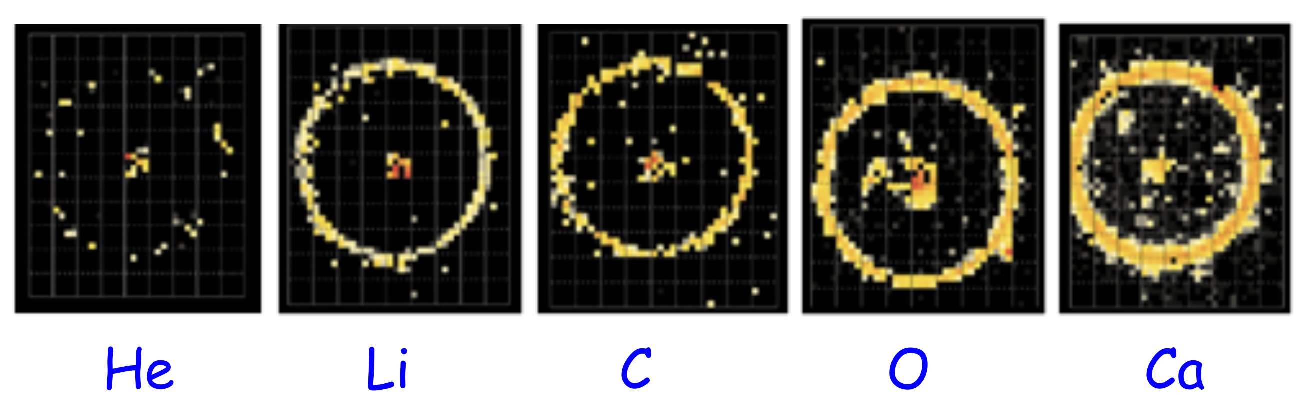
10,880 photosensors

21,760 Signal Pulses

?



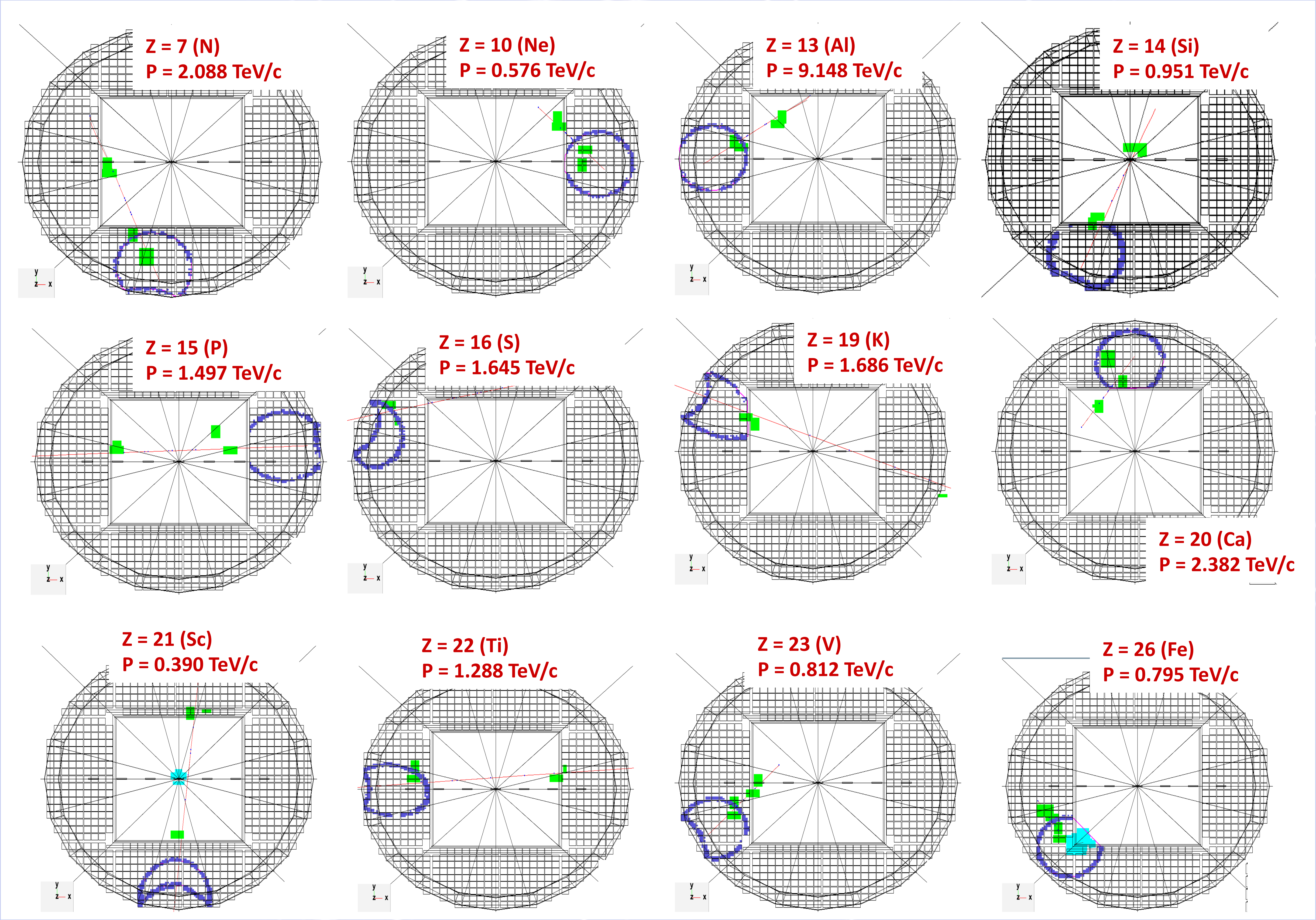
Single Event Displays from RICH test beam E=158GeV/n



σ(β)/β=0.1% @ β=1 (protons)

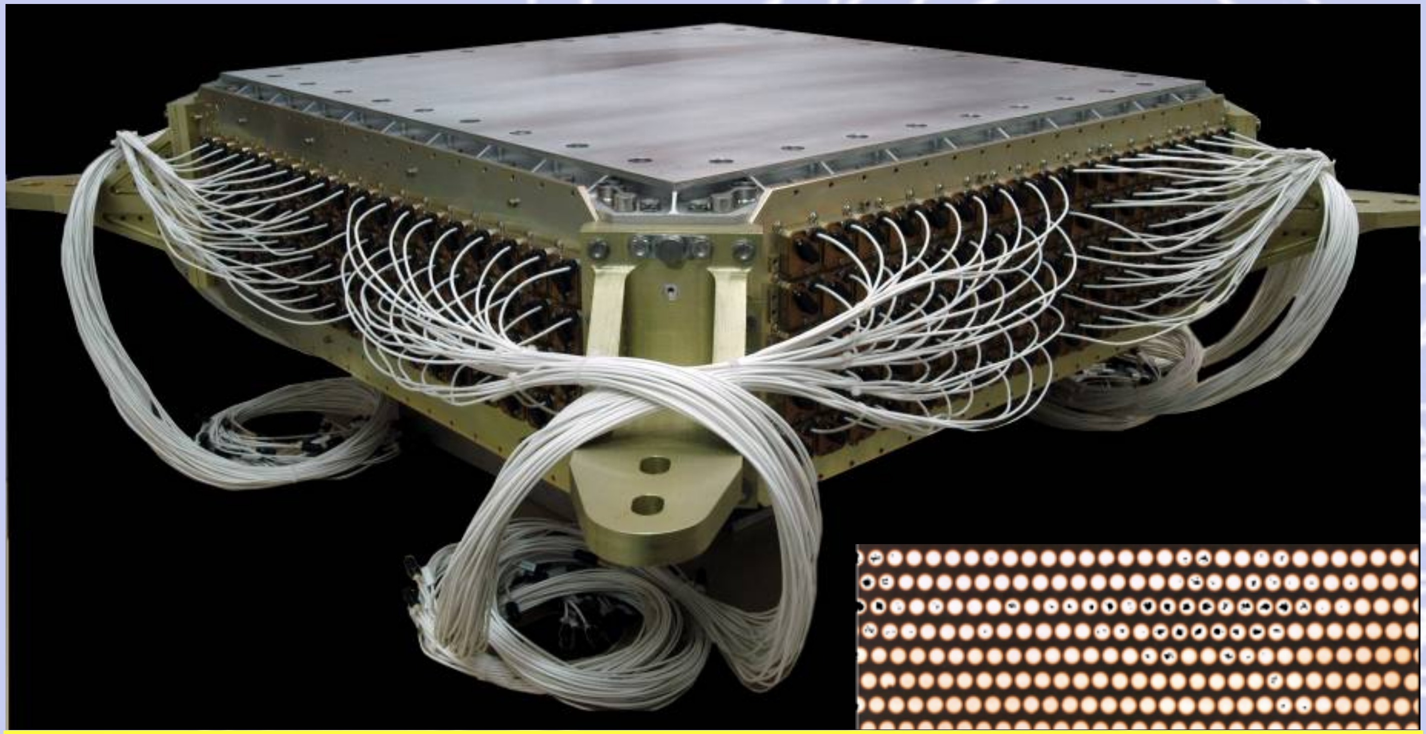
ΔZ ~ 0.2 up to Fe

Data from ISS: Nuclei identification from RICH

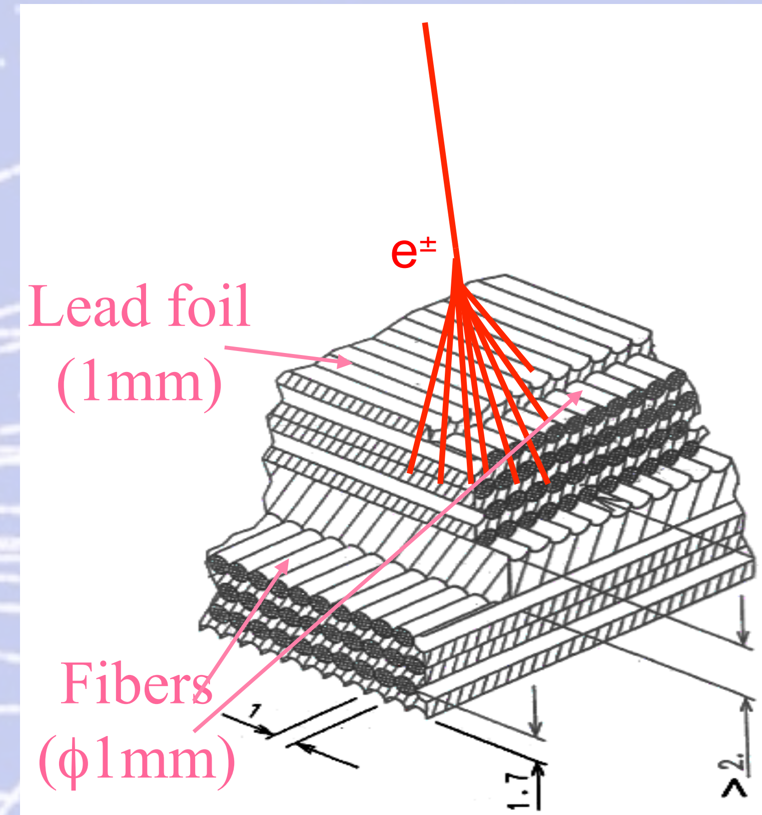


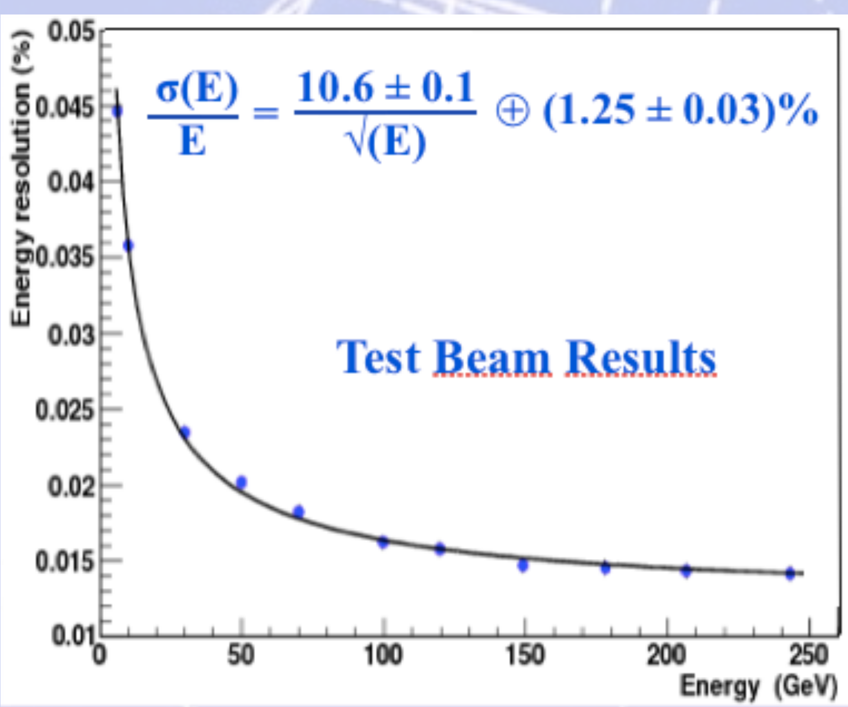
Calorimeter (ECAL)

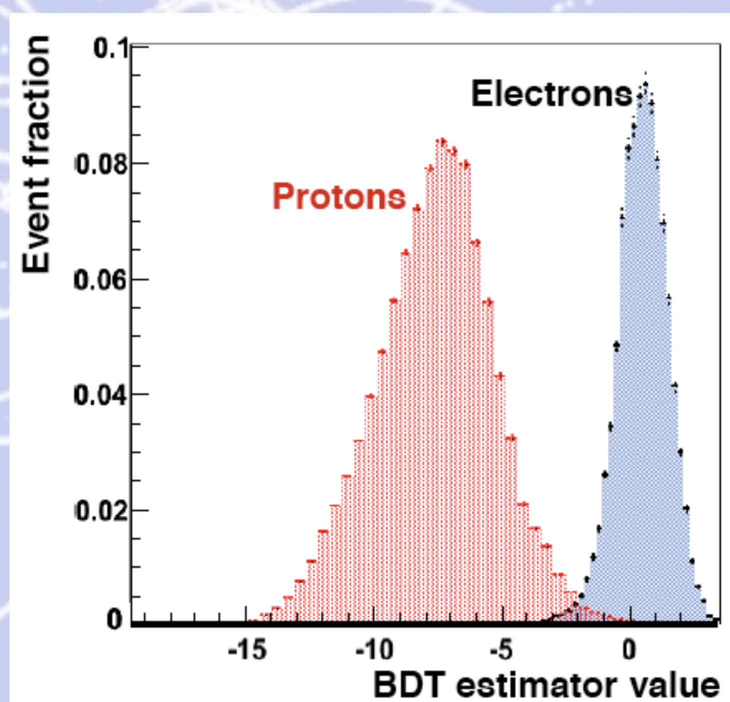
A precision, 17 X_0 , TeV, 3-dimensional measurement of the directions and energies of light rays and electrons

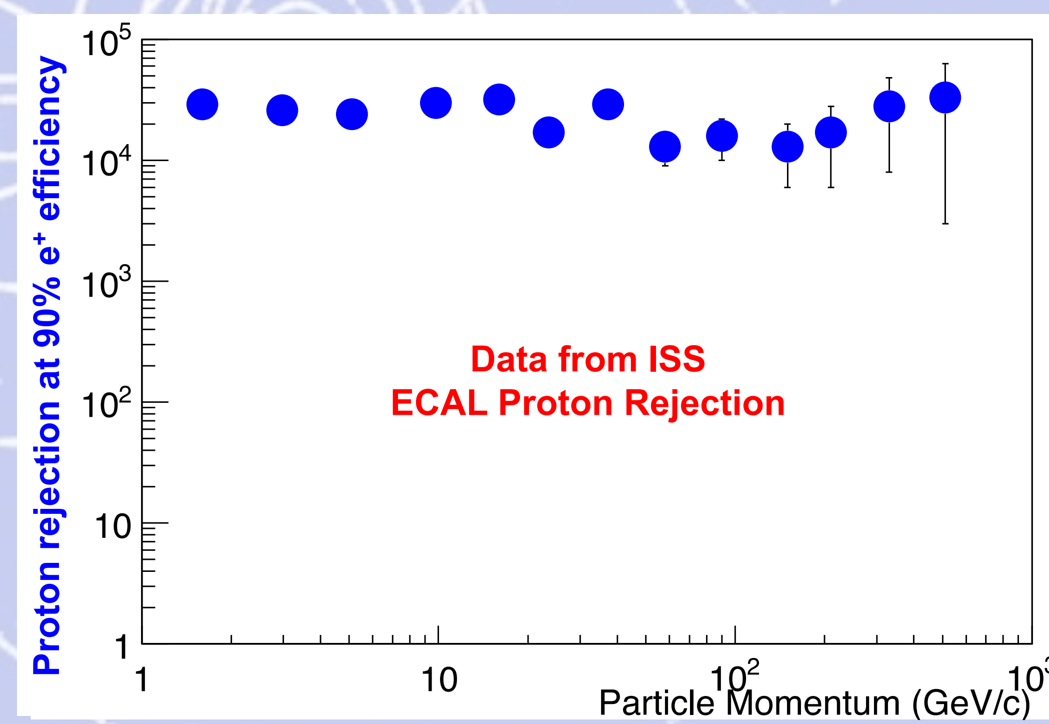


10 000 fibers, φ = 1 mm distributed uniformly inside 1,200 lb of lead









AMS electronics

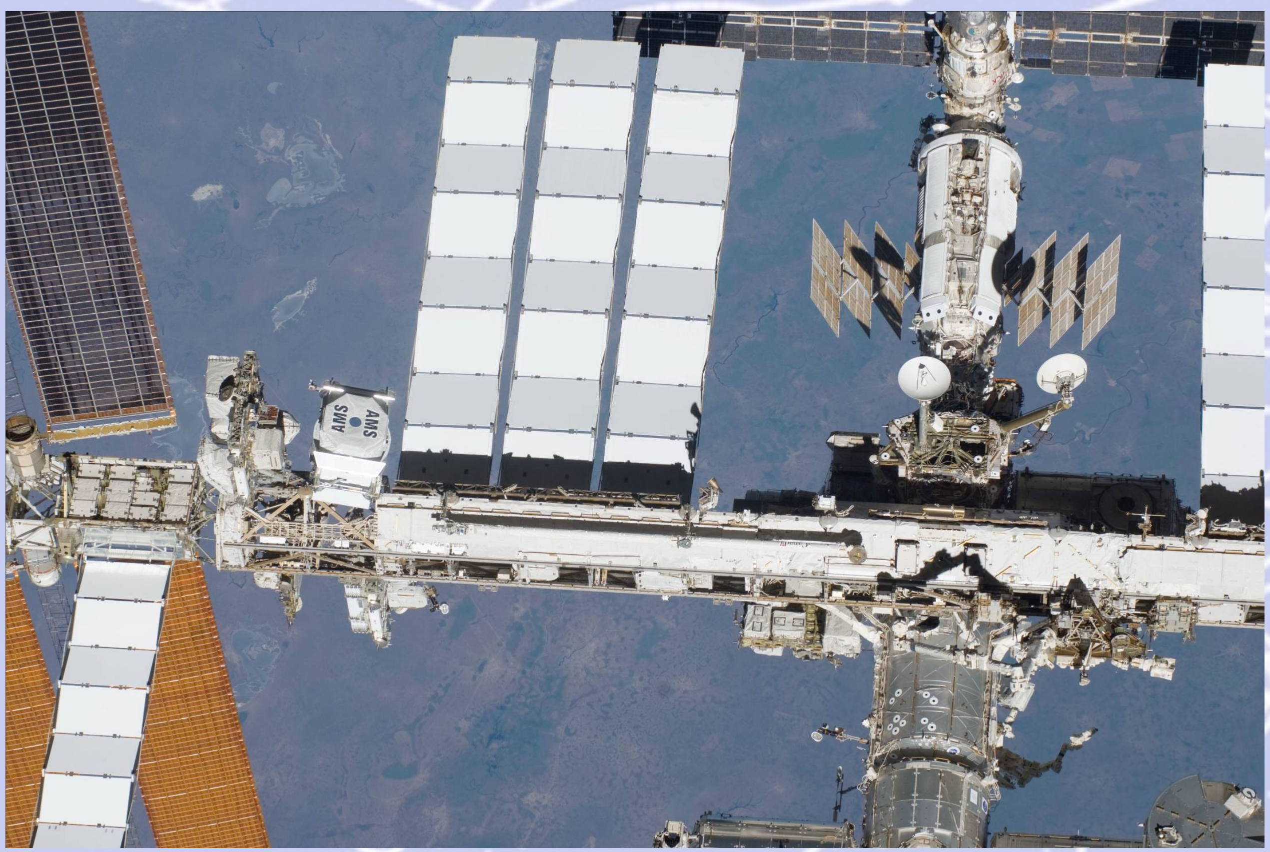
650 processors,
300,000 channels.
up to 400% redundancy

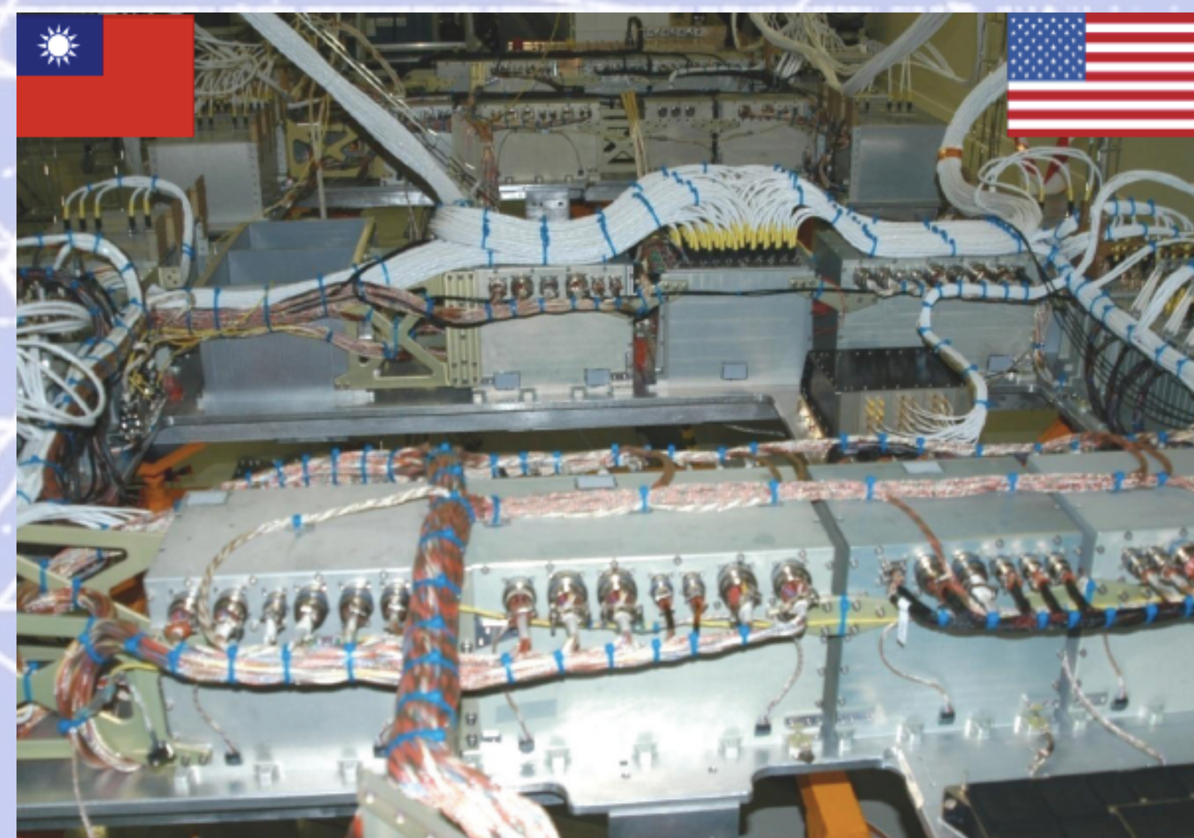
Reduce data volume
7 Gbit/s to 10 Mbit/s

To read out 300,000 channels at up to 2 KHz, a large set of computers (650) which are programmable from the POCC have been developed.

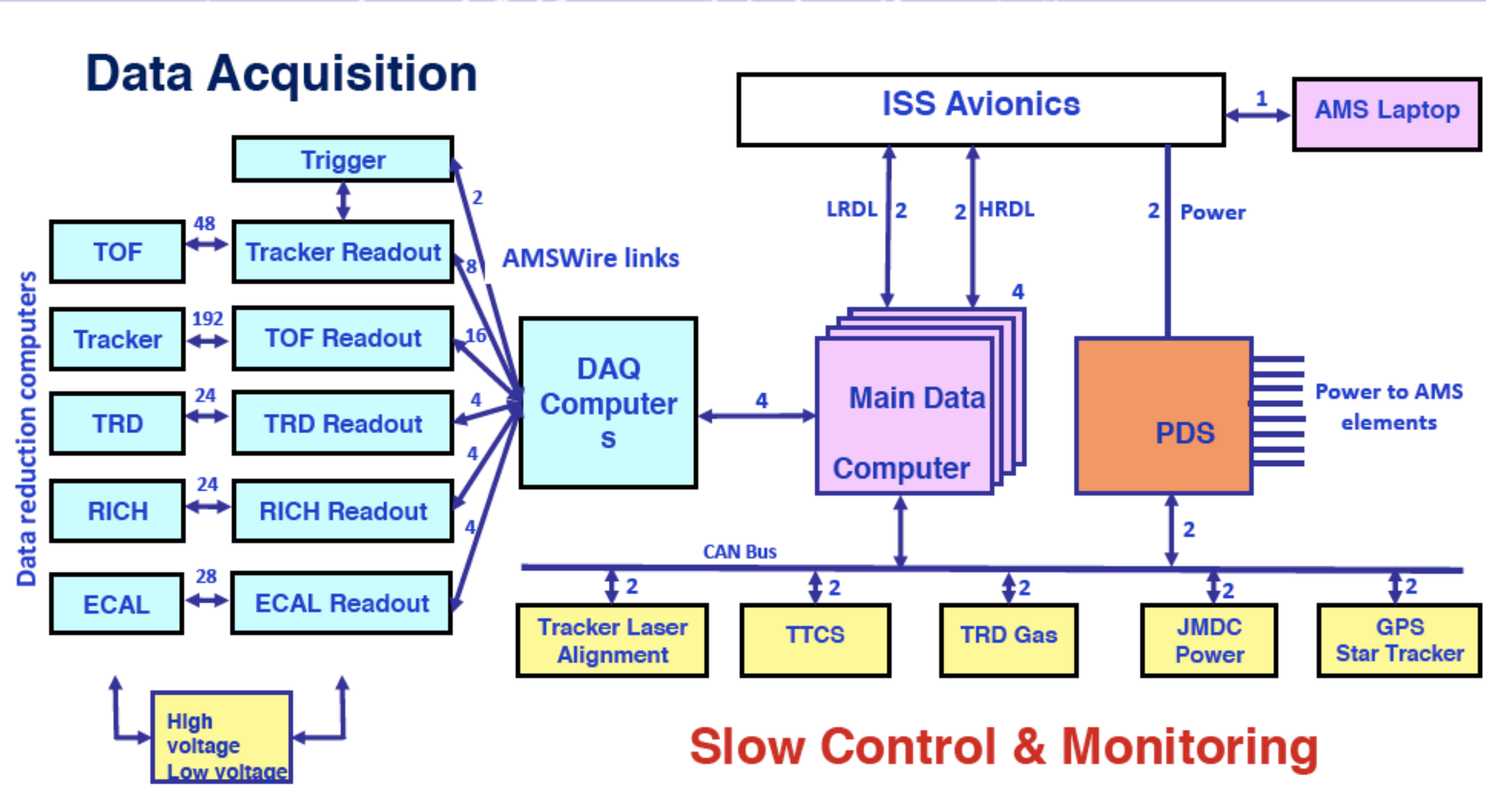
All the different detectors are readout with up to 400% redundancy.

Hundreds of these computers are interconnected in a tree like structure with an 100 MBit/s serial link.





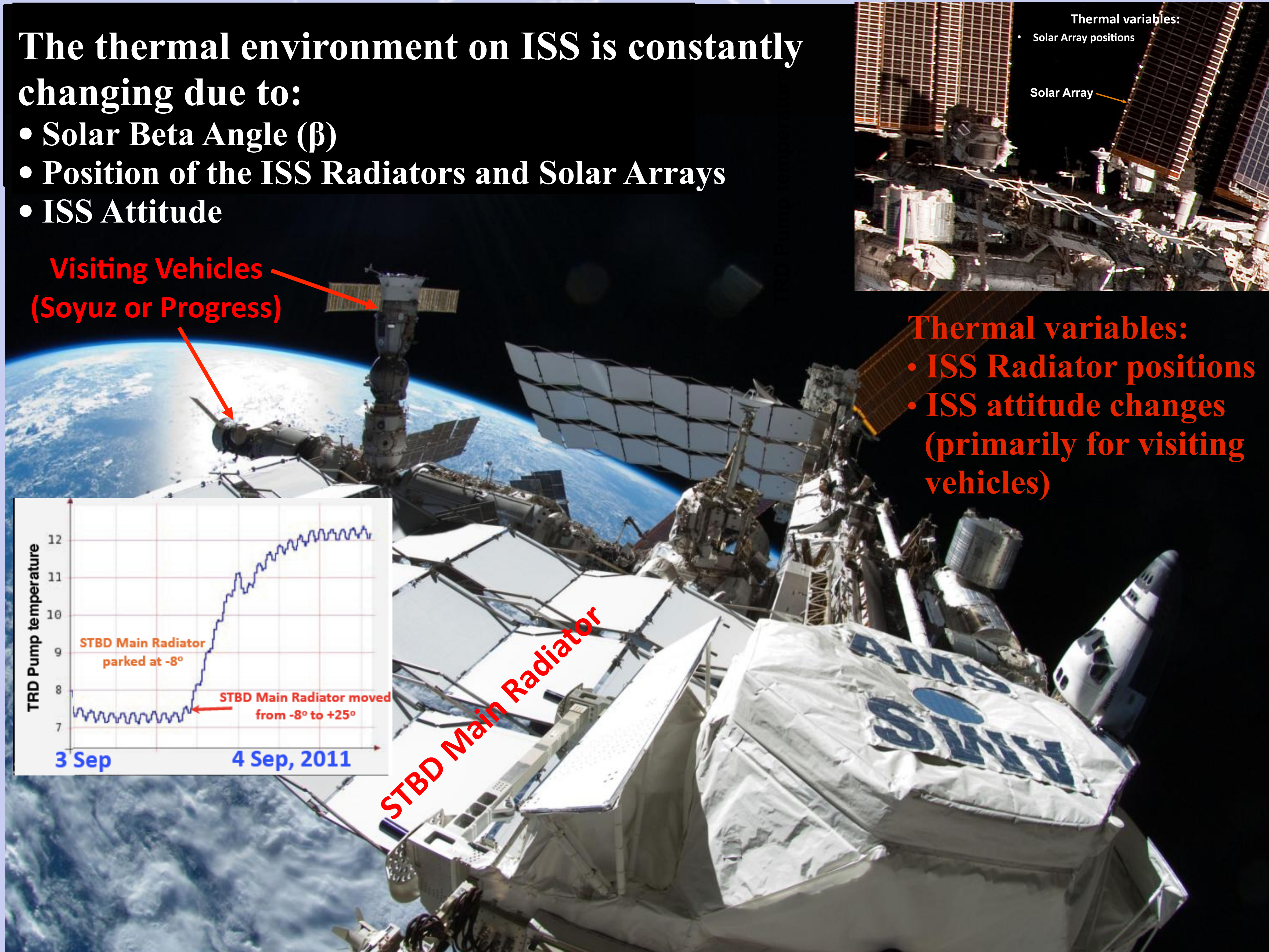
AMS electronics



Thermal Control is the most challenging task in the operation of AMS

The thermal environment on ISS is constantly changing due to:

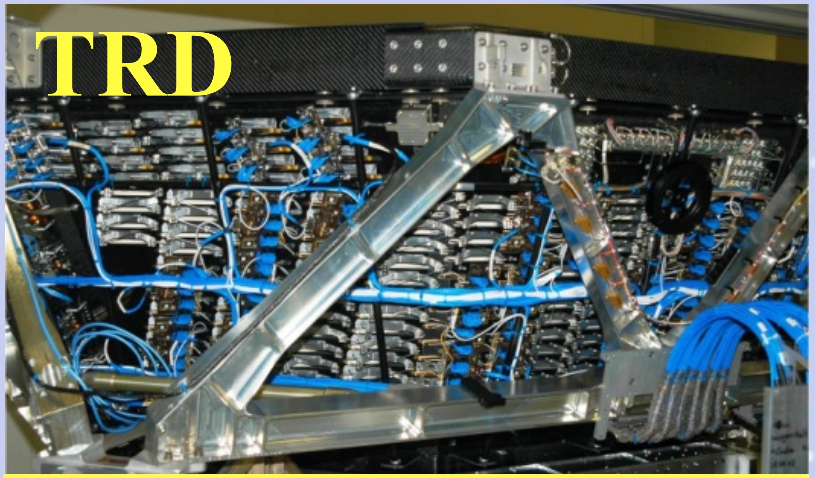
- Solar Beta Angle (β)
- Position of the ISS Radiators and Solar Arrays
- ISS Attitude



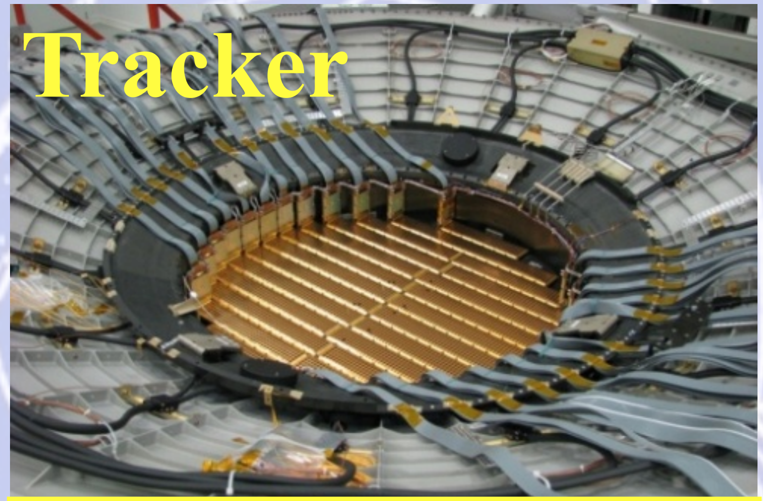
Thermal variables:

- ISS Radiator positions
- ISS attitude changes (primarily for visiting vehicles)

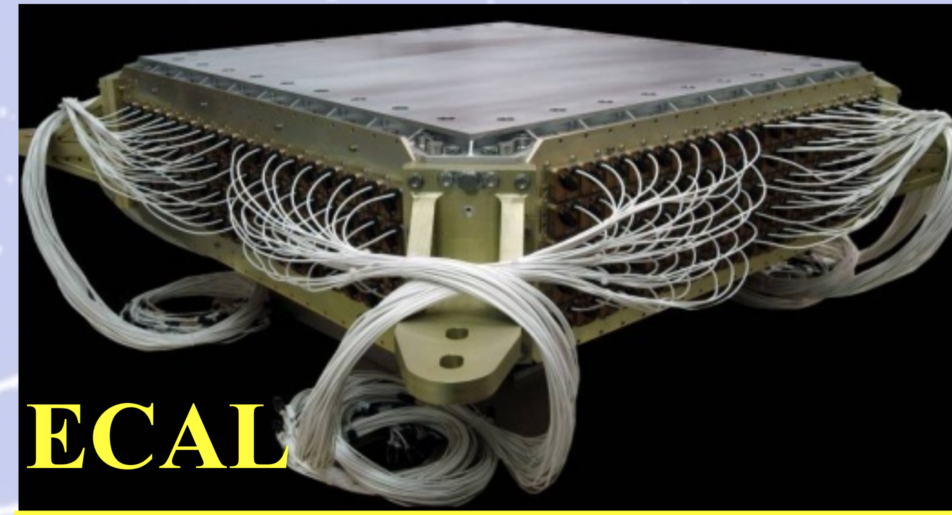
AMS Flight Electronics for Thermal Control



24 Heaters, 8 Pressure Sensors
482 Temperature Sensors

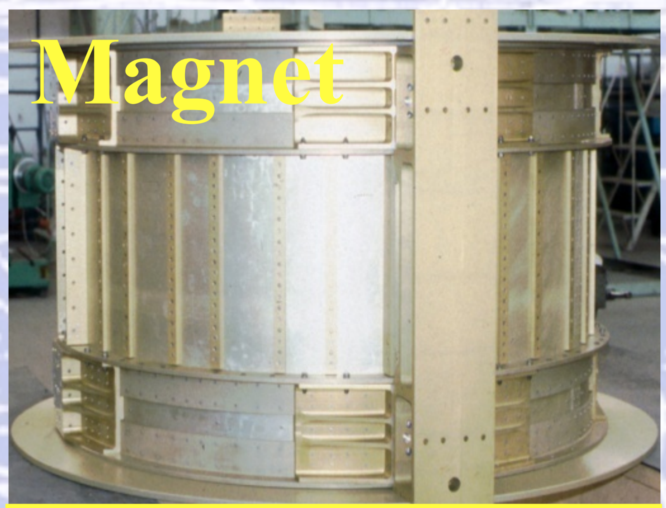


4 -Pressure Sensors, 32 Heaters
142 Temperature Sensors

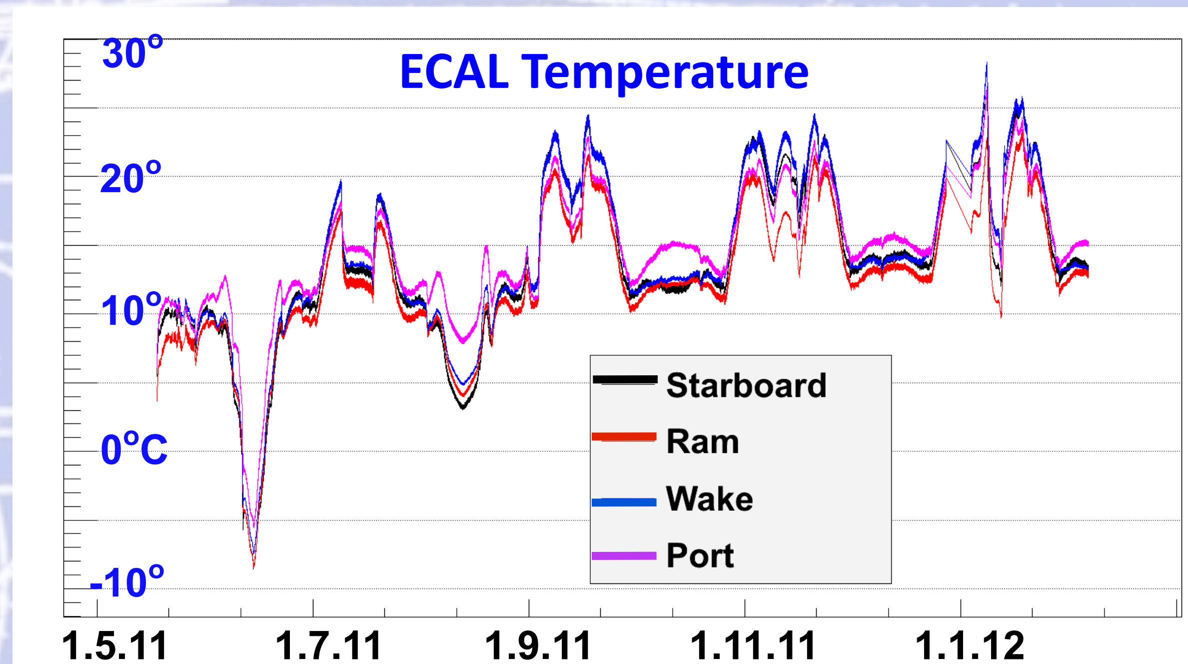


80 Temperature Sensors

64 Temperature Sensors



68 Temperature Sensors



96 Temperature Sensors

Over 1,100 temperature sensors and 298 heaters are monitored around the clock in the AMS POCC to assure components stay within thermal limits and avoid permanent damage.

Appendice 2

(Un po' di teoria)

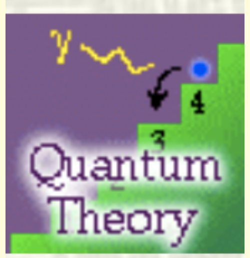
Particle Physics Timeline

For over two thousands years people have thought about fundamental particles from which all matter is made.

Starting with the gradual development of atomic theory, followed by a deeper understanding of the quantized atom, leading to the recent theory of the Standard Model.

Earliest times - 1550 AD: The Ancients

1550 - 1900 : The Scientific Revolution and Classical Mechanics

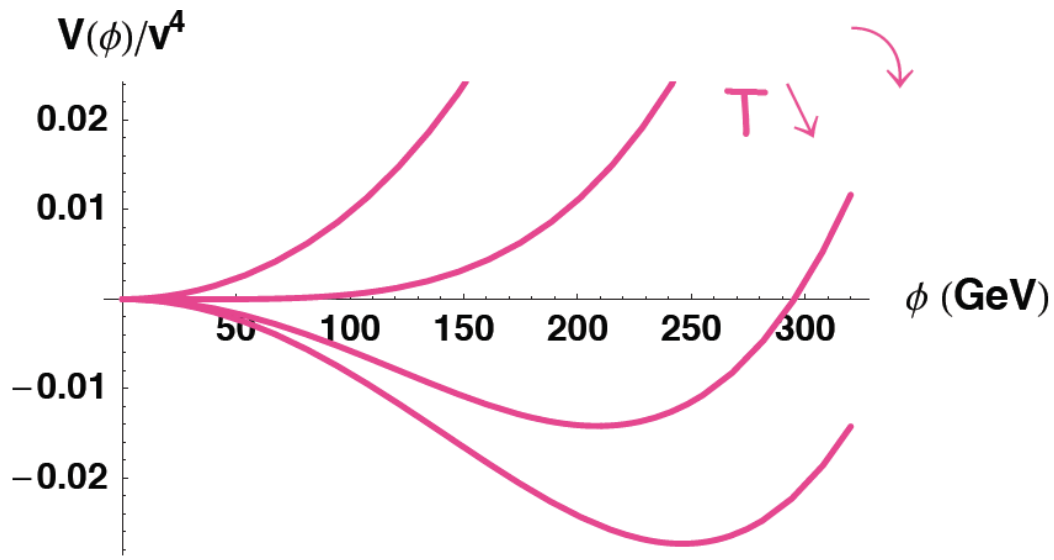


1900 - 1964 : Quantum Theory

1964 - Present: The Modern View (the Standard Model)

The (adhoc) Higgs Mechanism (a model without dynamics)

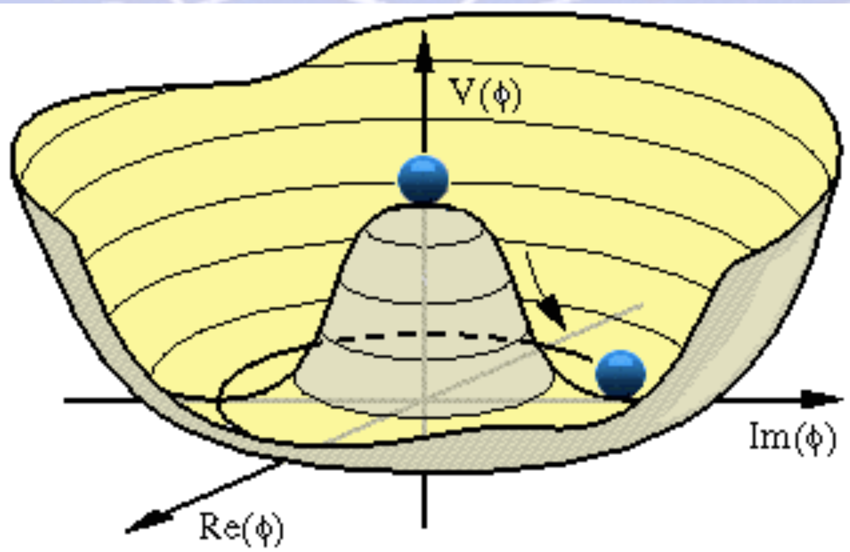
EW symmetry breaking is described by the condensation of a scalar field



$$\Phi = \begin{bmatrix} \phi^+ \\ \frac{v + H + i\varphi_Z}{\sqrt{2}} \end{bmatrix}$$

Background value, Higgs medium

Higgs boson: excitation of the higgs medium



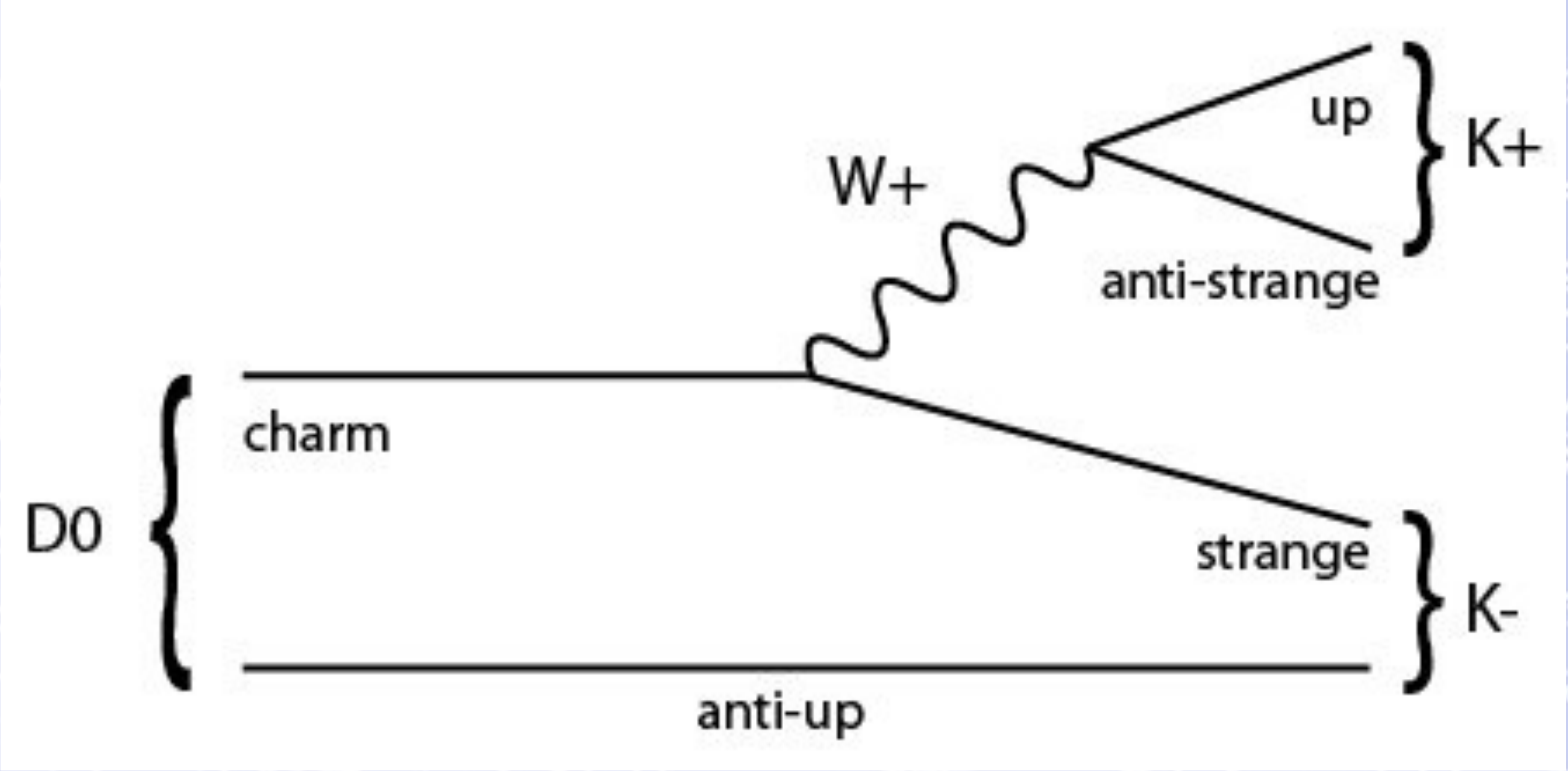
$$V(\Phi) = \frac{\mu^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}\Phi^\dagger\Phi$$

Why is μ^2 negative ?

The Higgs selects a vacuum state by developing a non zero background value.
When it does so, it gives mass to SM particles it couples to.

We do not know what makes the Higgs condensate.
We ARRANGE the Higgs potential so that the Higgs condensates but this is just a parametrization that we are unable to explain dynamically.

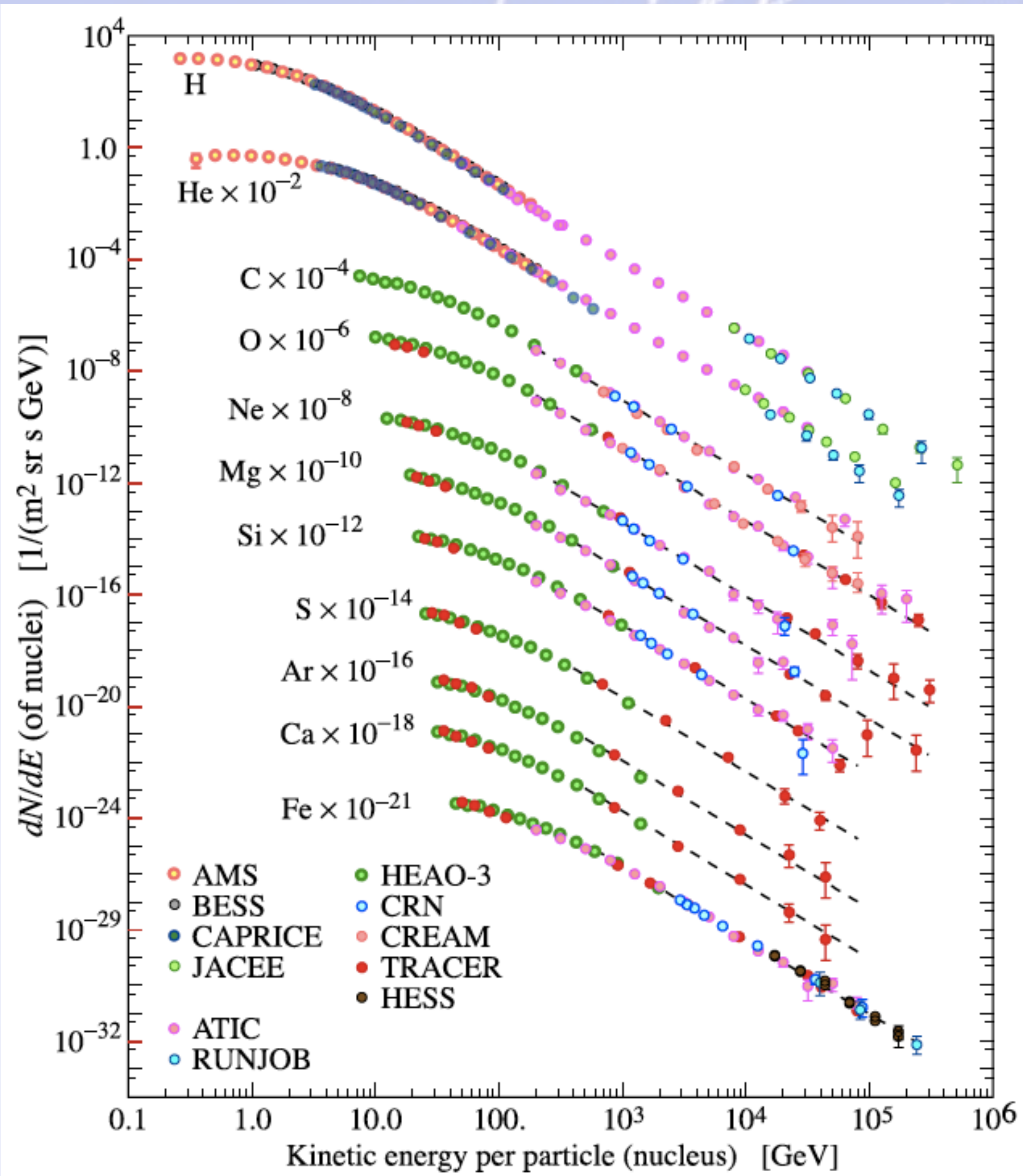
D^0 meson decay at LHCb



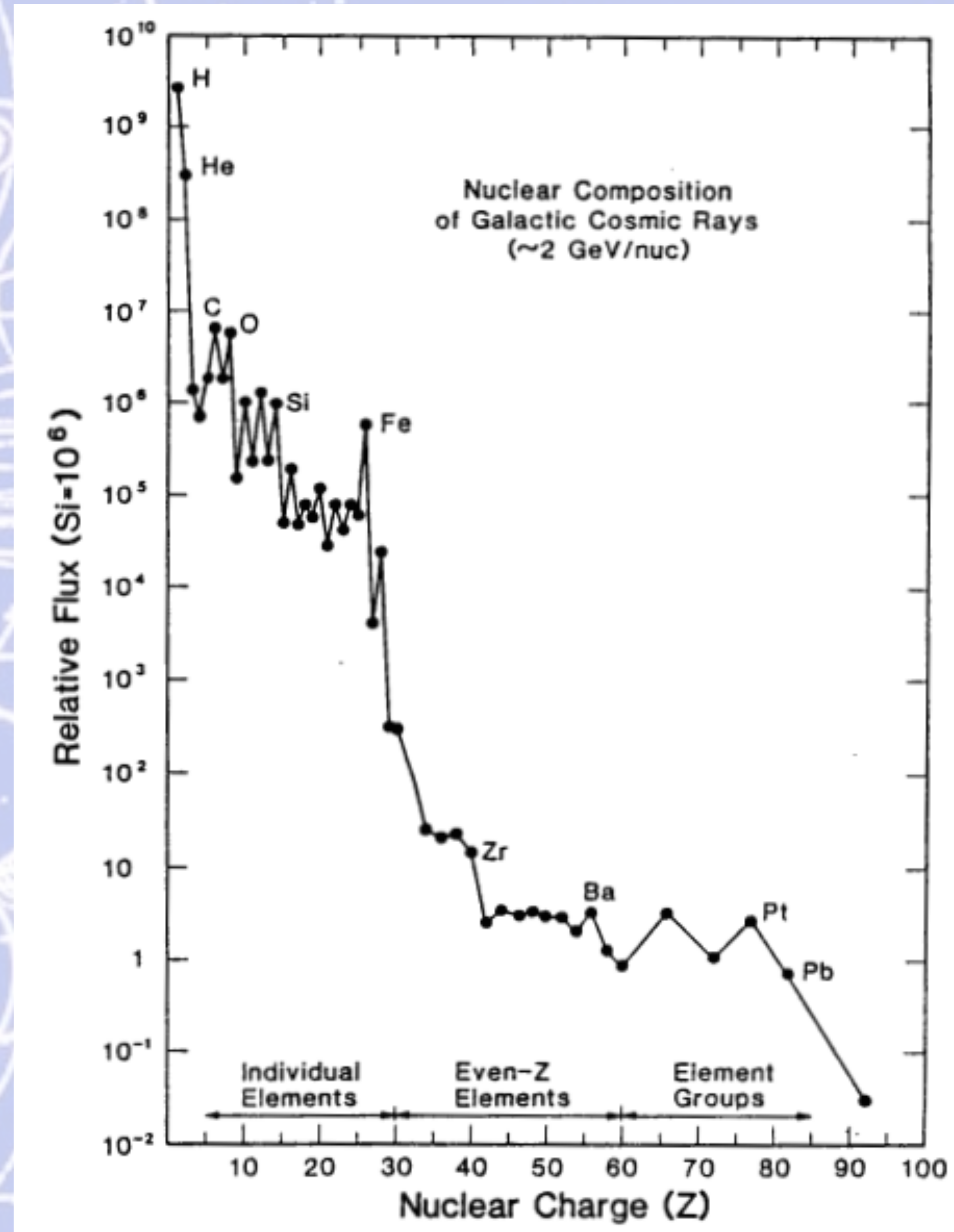
Appendice 3

(I raggi cosmici)

Abundance of different particles (➔ *identification)*



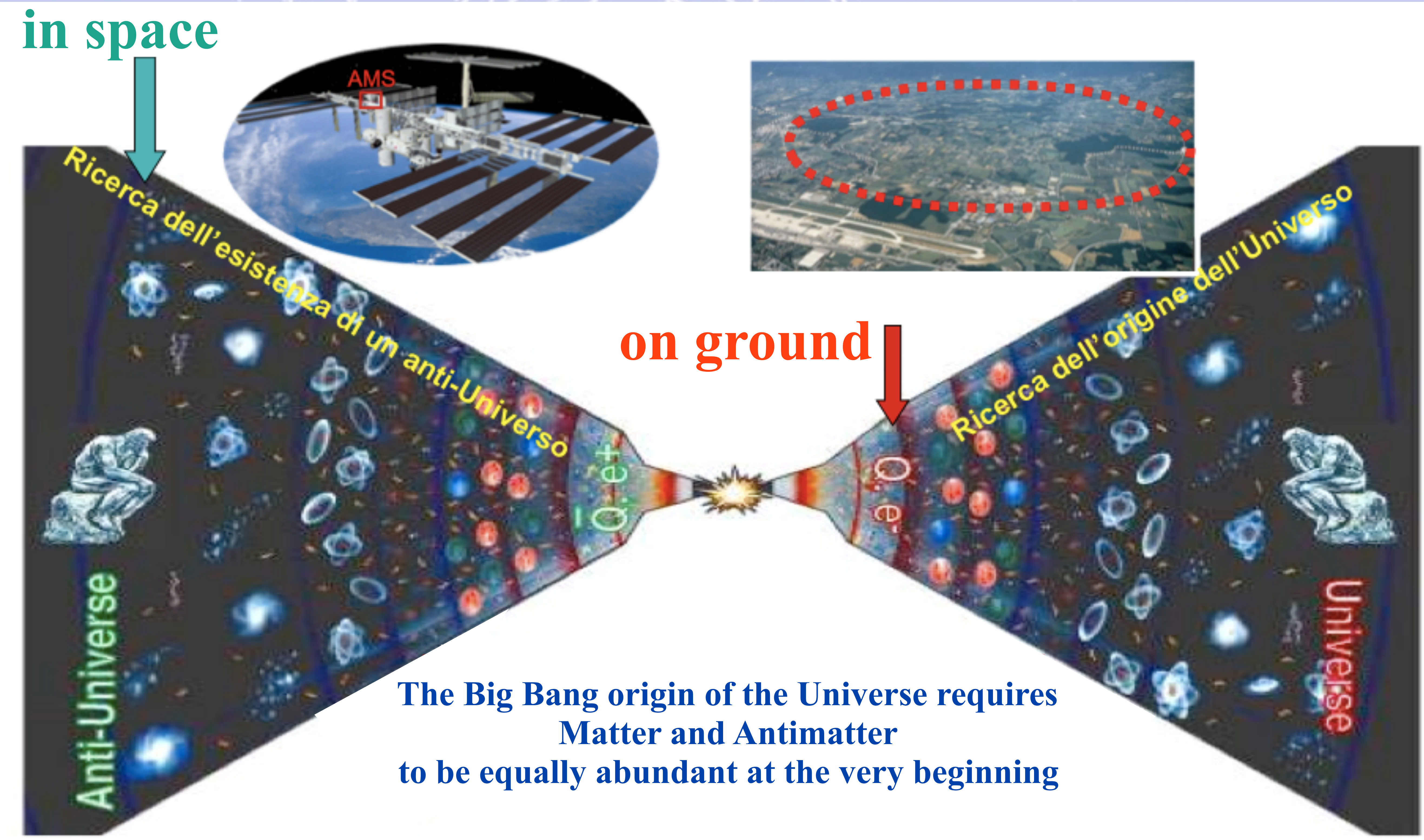
Abundance of different nuclei (elements)



Appendice 4

(L'antimateria)

Physics of AMS: Search for Antimatter



Physics of AMS: Search for Antimatter Universe

Experimental work on Antimatter in the Universe

Direct search

Search for Baryogenesis

New CP
BELLE
BaBar
(sin 2β= 0.672±0.023 consistent with SM)
FNAL KTeV
(Re(ε'/ ε) = (19.2±2.1)*10^{-4})
CERN NA-48
CDF, D0

Proton decay
Super K
(Tp > 6.6 * 10^{33} years)

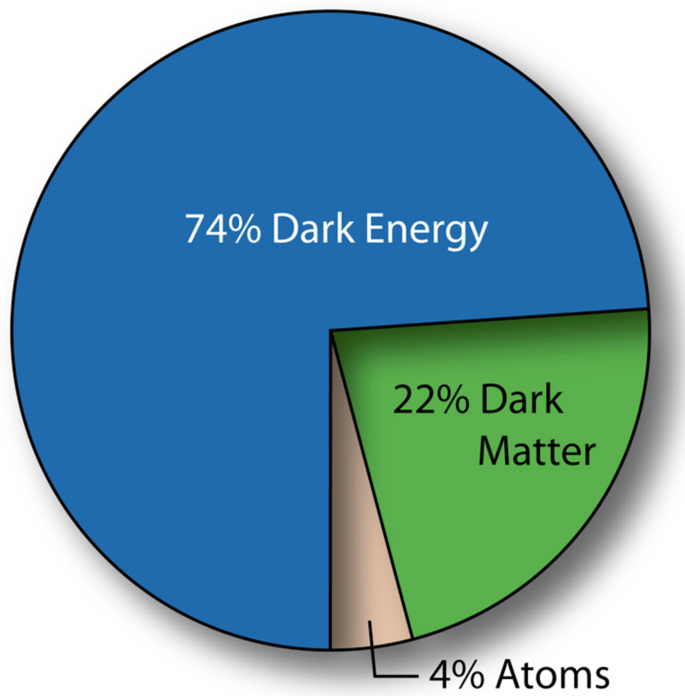
AMS

LHC-b, ATLAS,CMS

Increase in sensitivity: x 10^3 - 10^6
Increase in energy to ~TeV

No explanation found for the absence of antimatter (no reason why antimatter should not exist)

Are Dark Matter and baryon abundances related ?



Baryonic asymmetry characterized in terms of the baryon to photon ratio

$$\frac{n_B - \bar{n}_B}{n_\gamma} \sim 6\times10^{-10}$$

$\Omega_{DM} \approx$ 5-6 $\Omega_{baryons}$

if $n_{DM} - \bar{n}_{DM} \sim n_B - \bar{n}_B$

$$\frac{\Omega_{DM}}{\Omega_{baryons}} \sim C \frac{m_{DM}}{m_{baryons}}$$

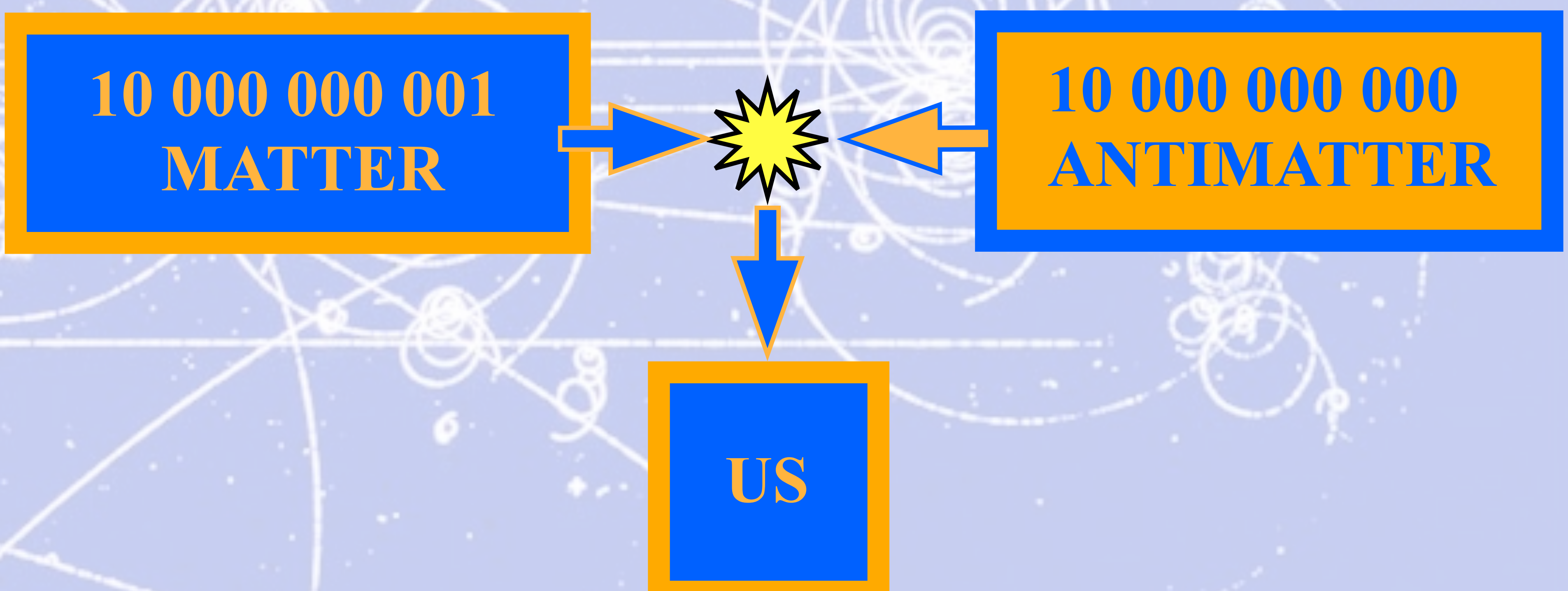
Does this indicate a common dynamics?

Sakharov's conditions for baryogenesis (1967)

1) **Baryon number violation**
   (we need a process which can turn antimatter into matter)

2) **C (charge conjugation) and CP (charge conjugation × Parity) violation.**
   (we need to prefer matter over antimatter)

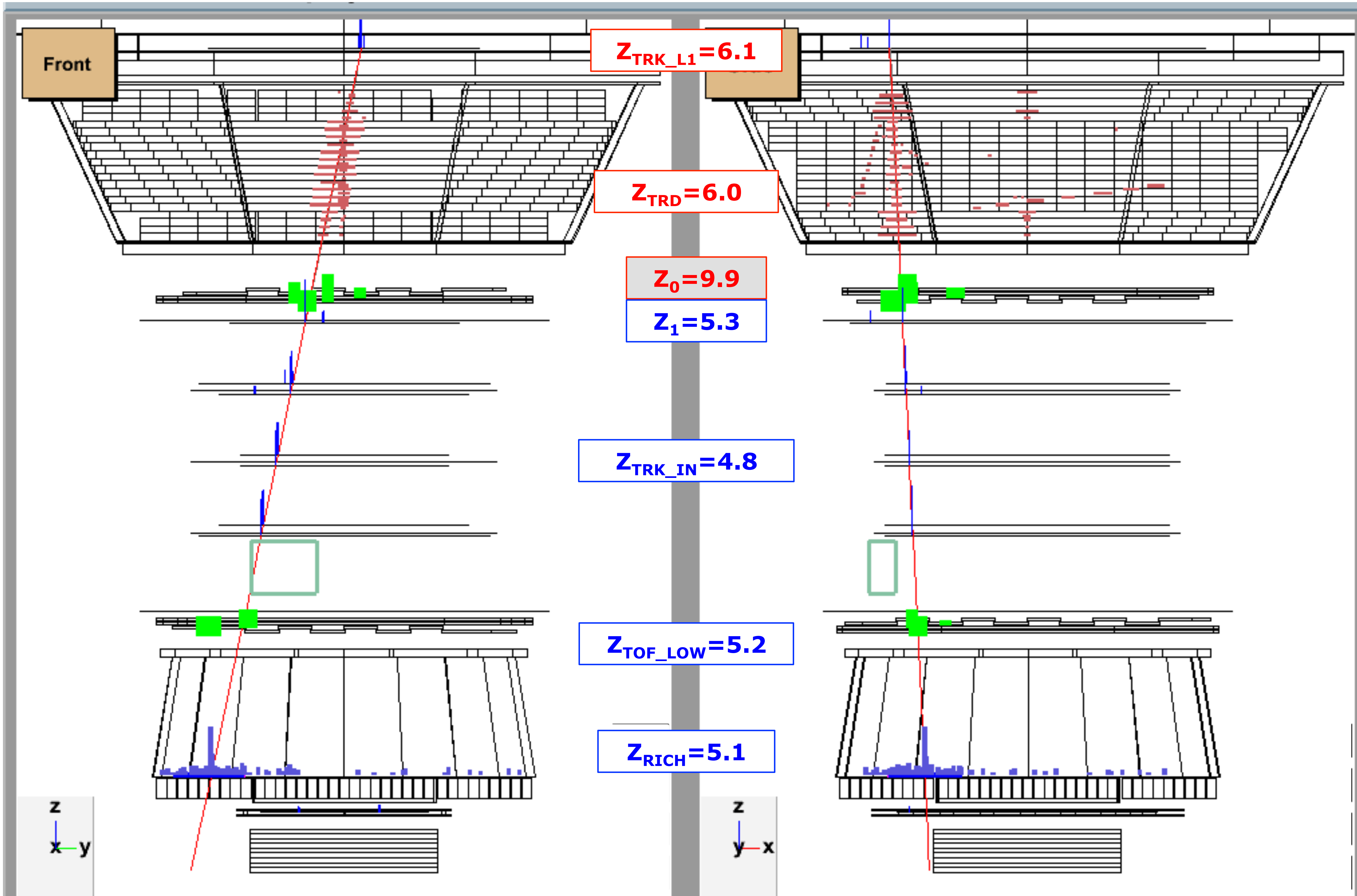
3) **Loss of thermal equilibrium**
   (we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature, particles & antiparticles have the same mass , so no asymmetry can develop)



Appendice 5

(Rapporto Boro/Carbonio)

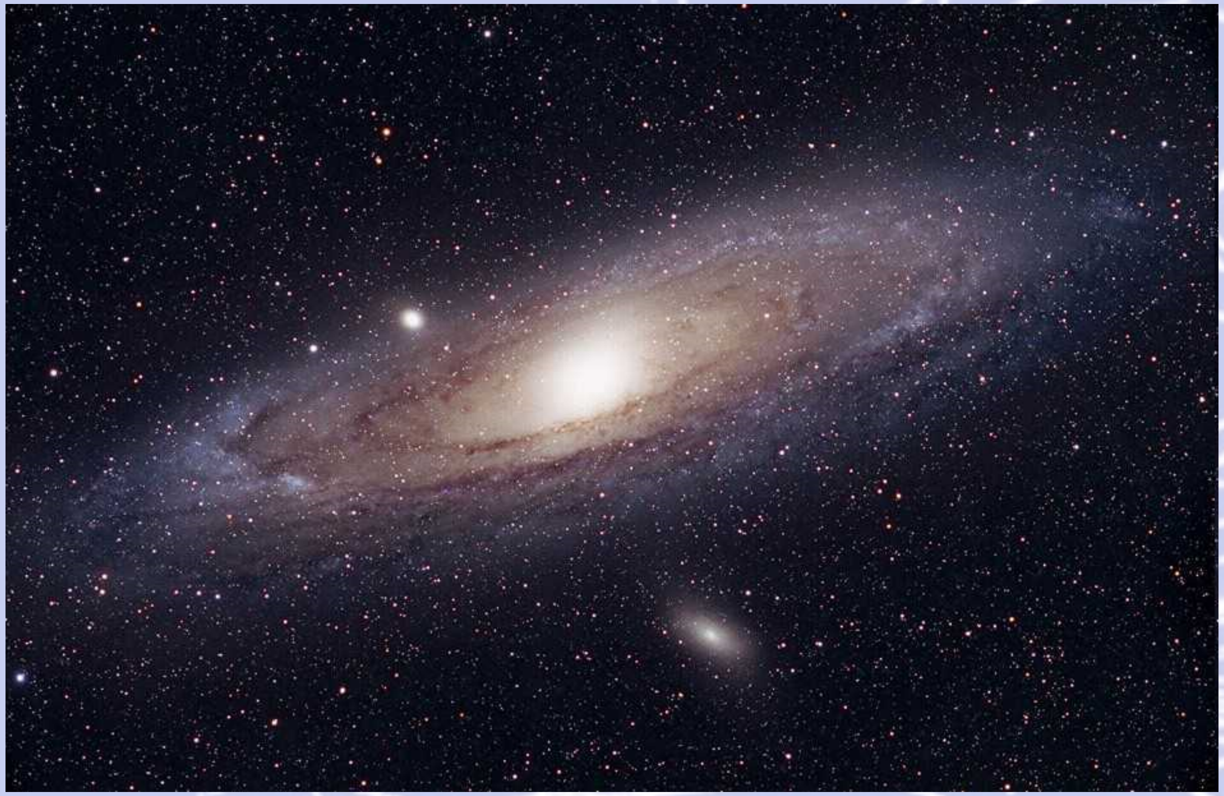
Carbon Fragmentation to Boron in Upper TOF
Rigidity 10.6 GV



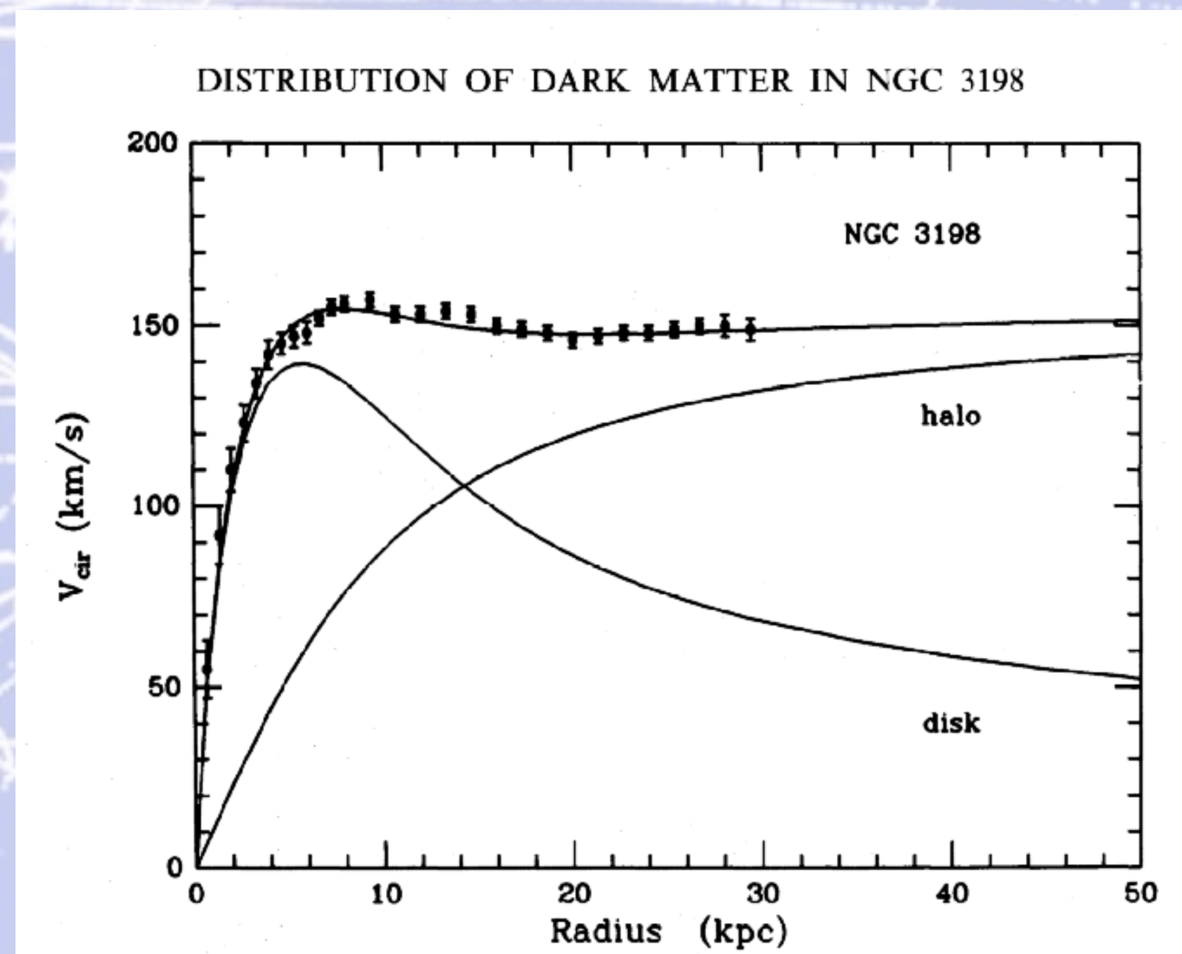
Appendice 6

(La materia Oscura)

Dark Matter



The velocity of stars lying at galaxies periphery indicate that there is much more matter in the galaxy than what we measure from visible stars.



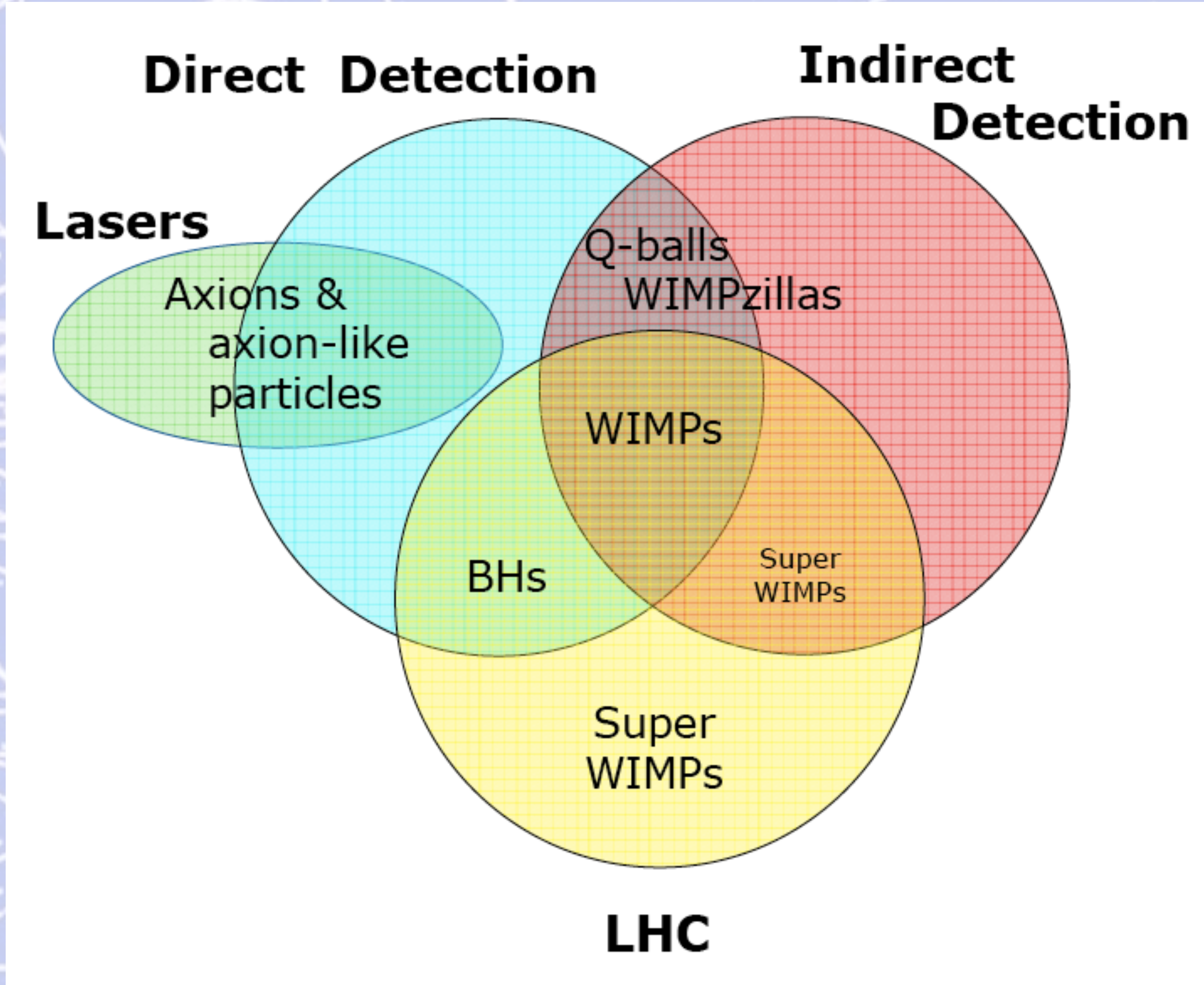
We don't know the nature of this new kind of matter we can only detect from its gravitational effects.

Several hypothesis exist to explain it.

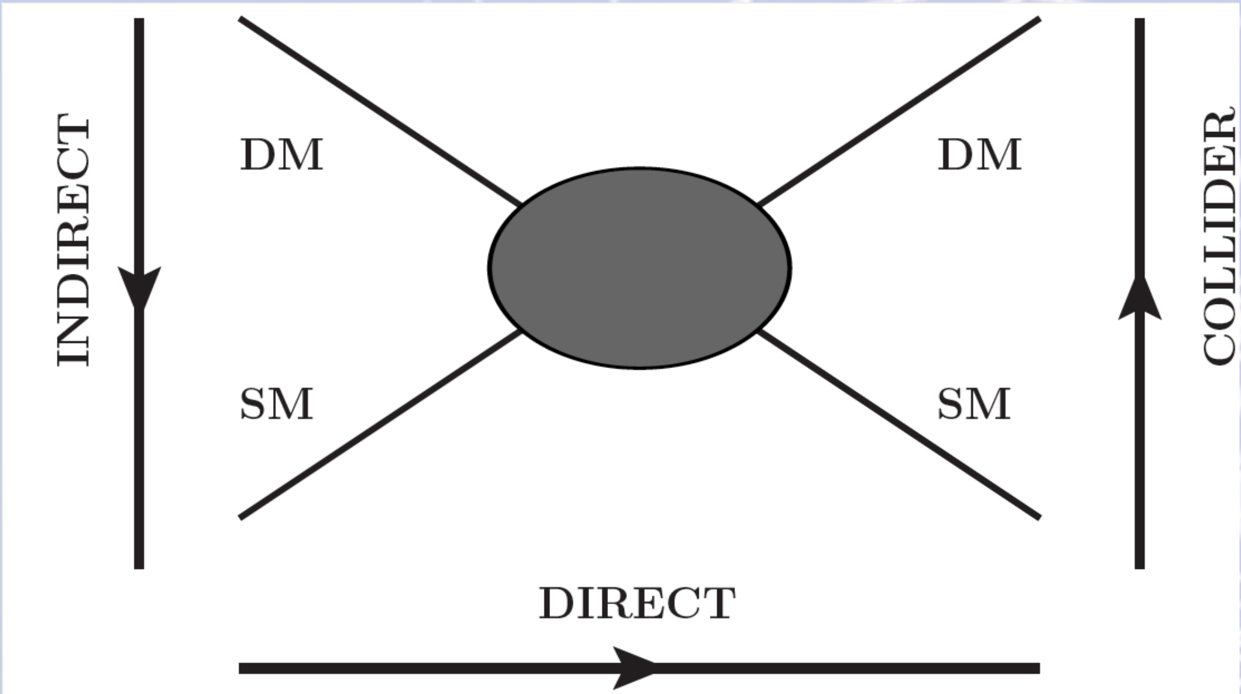
One of them tells that Dark Matter should be composed by supersymmetric particles not yer detected nowadays.

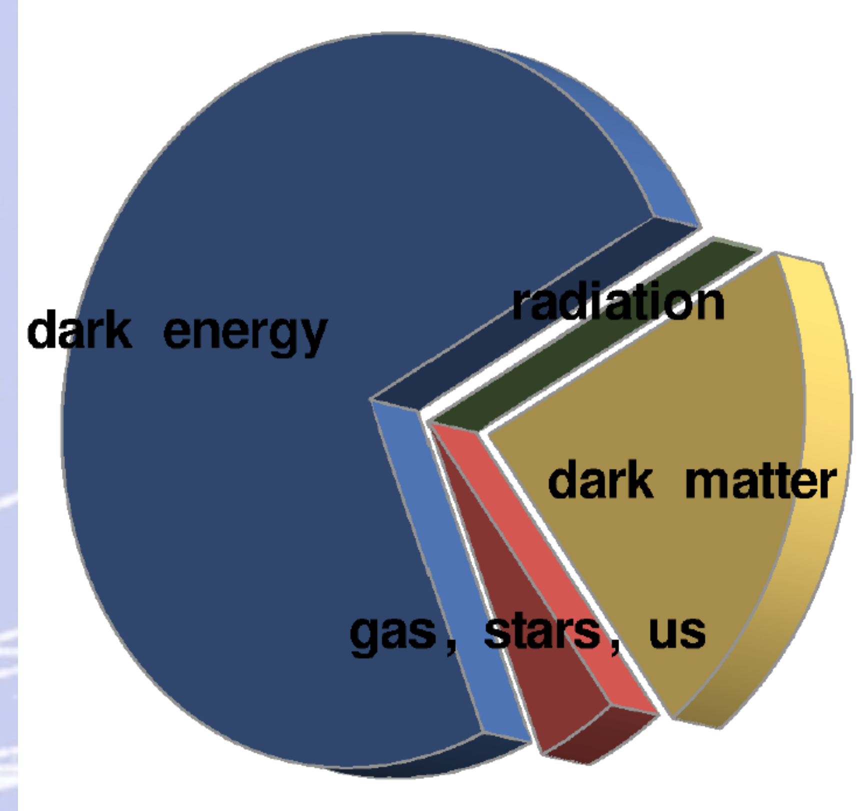
Dark Matter detection

- **WIMPs**
  - **Neutralinos**
  - **Kaluza-Klein particles**
  - **…….**
- **Axinos**
- **Super-WIMPs**
- **Axions**
- **Axion-like light bosons**
- **Sterile neutrinos**
- **Q-balls**
- **WIMPzillas**
- **Elementary BHs**



Ways of detecting dark matter



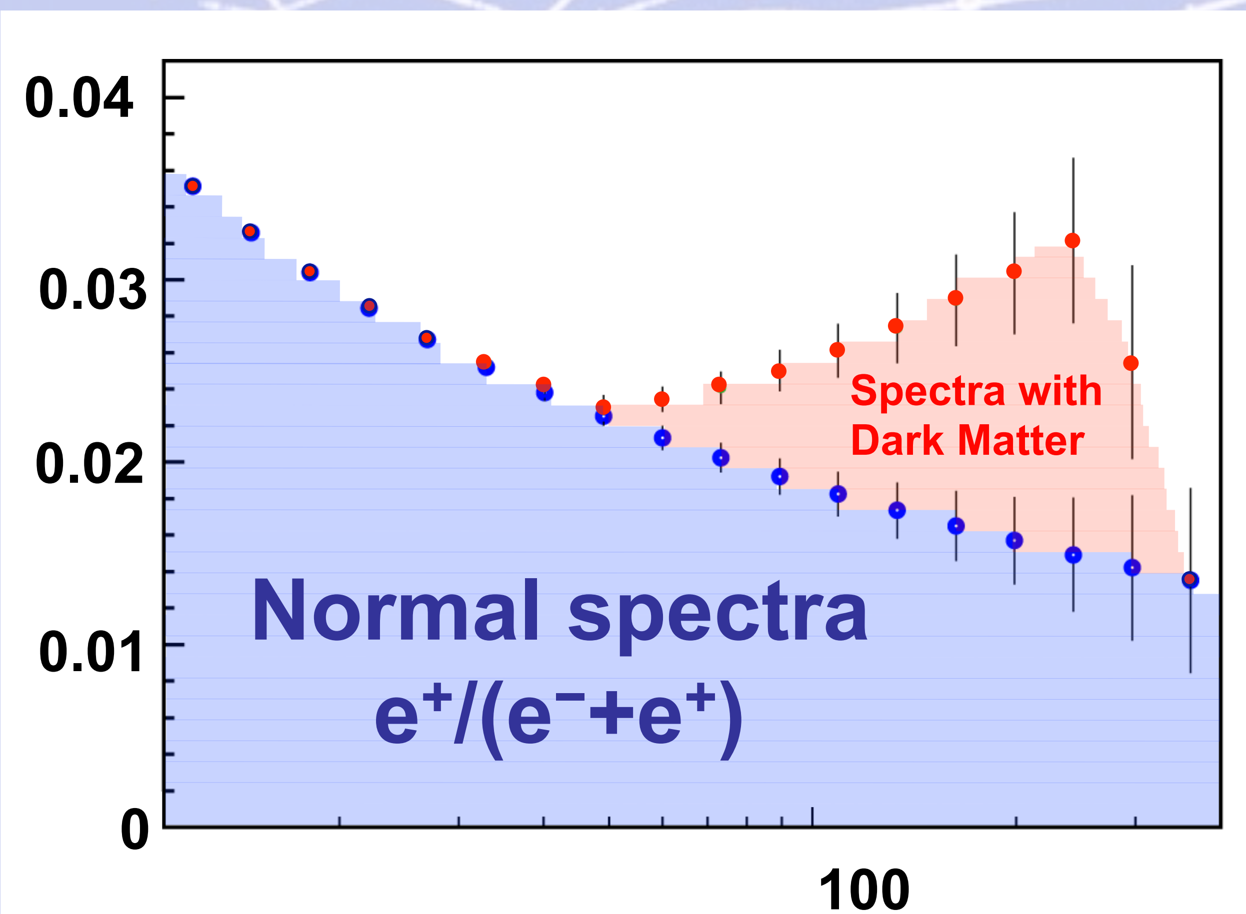


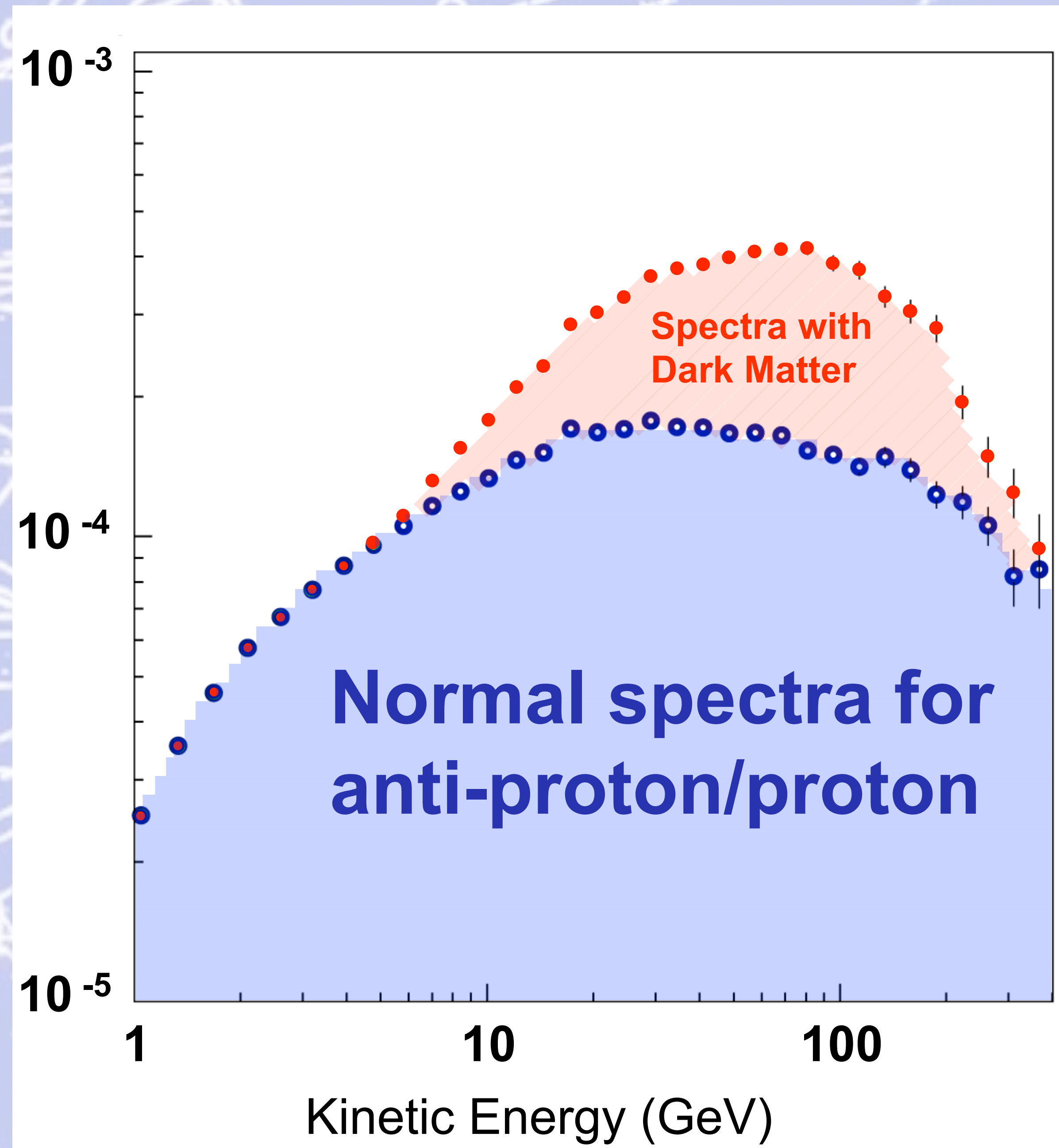
1 Direct detection.
2 Indirect detection: searching for products of annihilation.
High energy photons
- Space telescopes: COMPTEL, Fermi-LAT, AMS
- ACTs: HESS, Veritas, Magic.
Electrons/positrons: PAMELA, ATIC, Fermi-LAT, AMS, HESS, MAGIC.
Antiprotons: PAMELA, AMS.
Neutrinos: ANTARES, IceCube.
3 Collider searches: LHC.
4 Indirect2: CMB optical depth and anisotropies, IGM temperature and 21 cm - recombination and reionization observables, BBN.

Dark Matter: neutralino annihilation

Lets suppose the existence of massive particles (χ) which are their own anti-particles. If they meet they annihilate producing other particles and anti-particles thanks to the available energy.

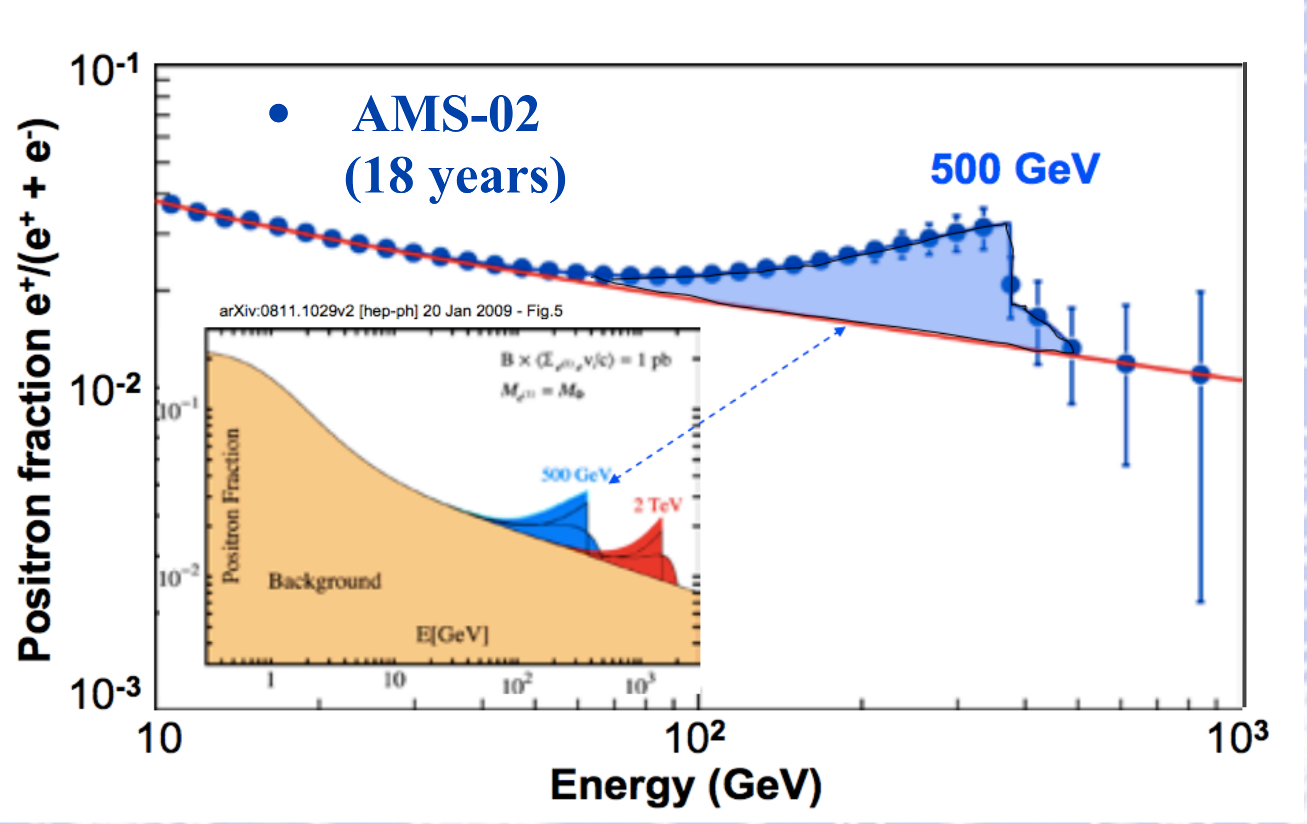
As a consequence, the cosmic rays spectrum will be modified. These anomalies can be searched in positrons or anti-protons spectra.





Physics of AMS: Search for Dark Matter

The lightest Kaluza-Klein state is an excellent dark matter candidate if standard model particles propagate in extra dimensions (universal extra dimensions)



Expected spectrum from collisions of 500 GeV Kaluza-Klein bosons based on Pontón and Randall model

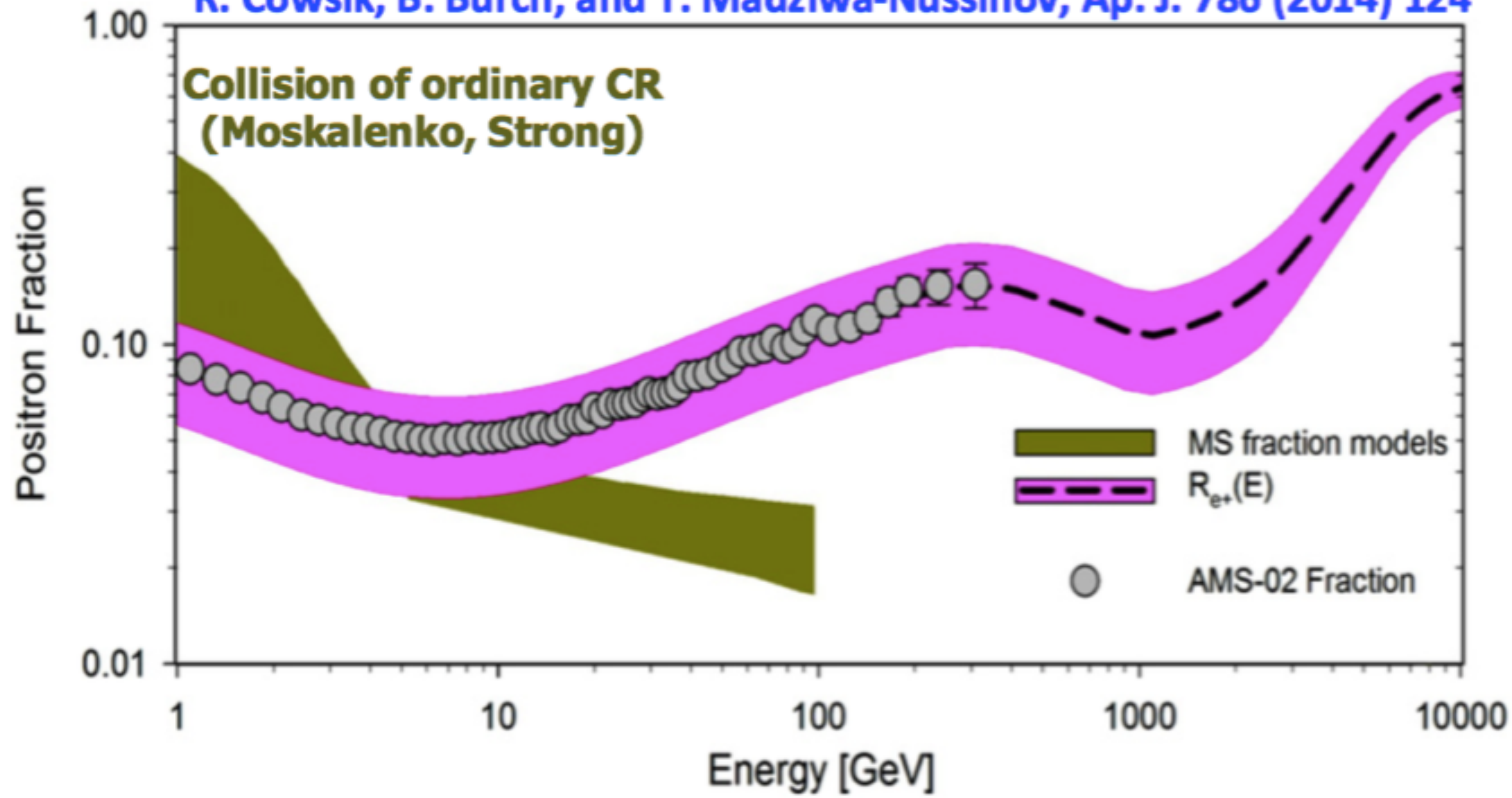
E.Pontón and L.Randall, preprint arXiv:0811.1029v2 (2009)

Un esempio di modello (1)

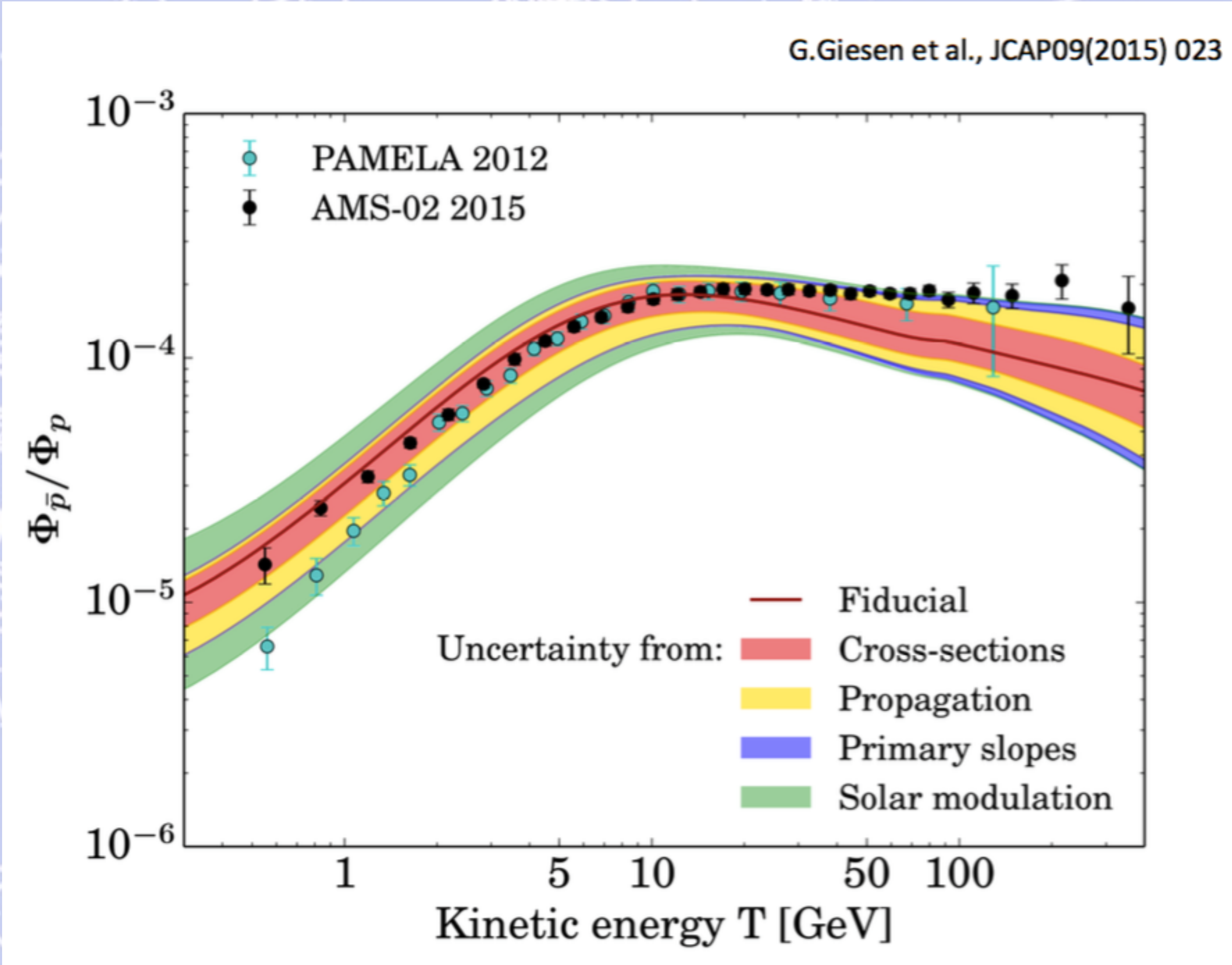
Theoretical models to explain the AMS positron fraction.
Among the 100's of models there are three classes:

a) dark matter
b) new forms of propagation
c) pulsars.

b) An example of new propagation:
R. Cowsik, B. Burch, and T. Madziwa-Nussinov, Ap. J. 786 (2014) 124



Un esempio di modello (2)

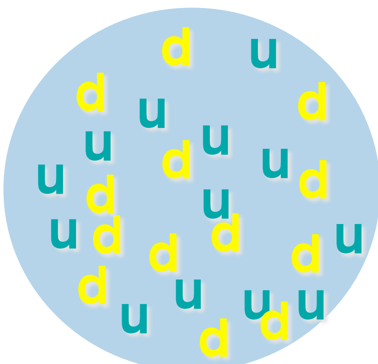


Appendice 7

(Materia "strana")

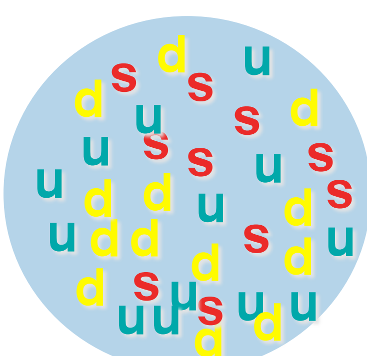
Search for Strangelets

All the known material on Earth is made out of u and d quarks



Diamond (Z/A ~ 0.5)

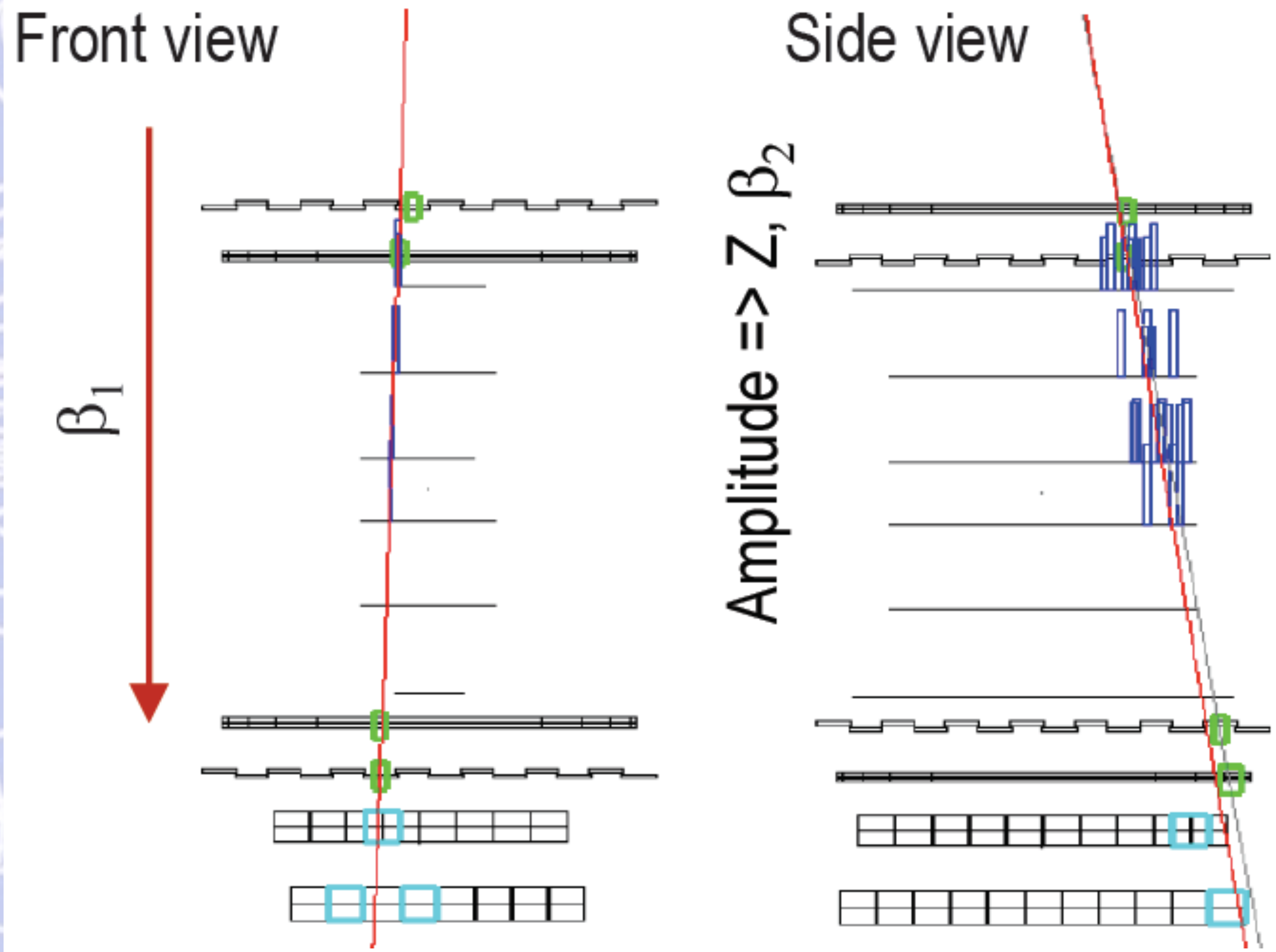
Is there material in the universe made up of u, d, & s quarks?



Strangelet (Z/A < 0.1)

This can be answered definitively by AMS.

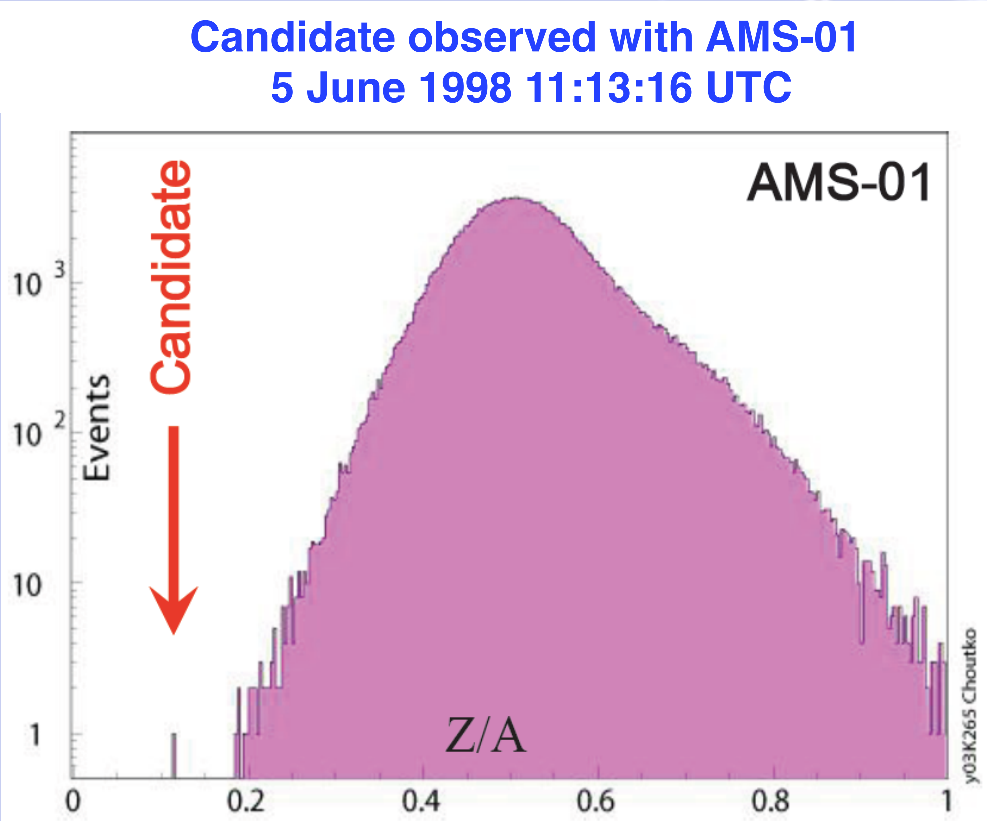
Candidate observed with AMS-01
5 June 1998 11:13:16 UTC

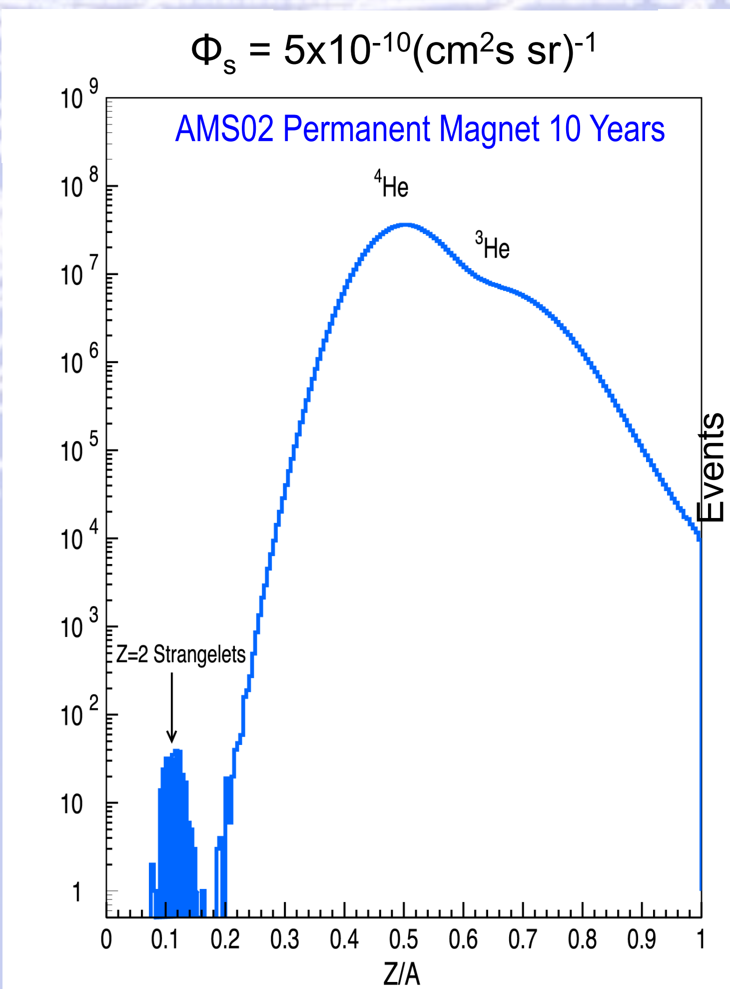


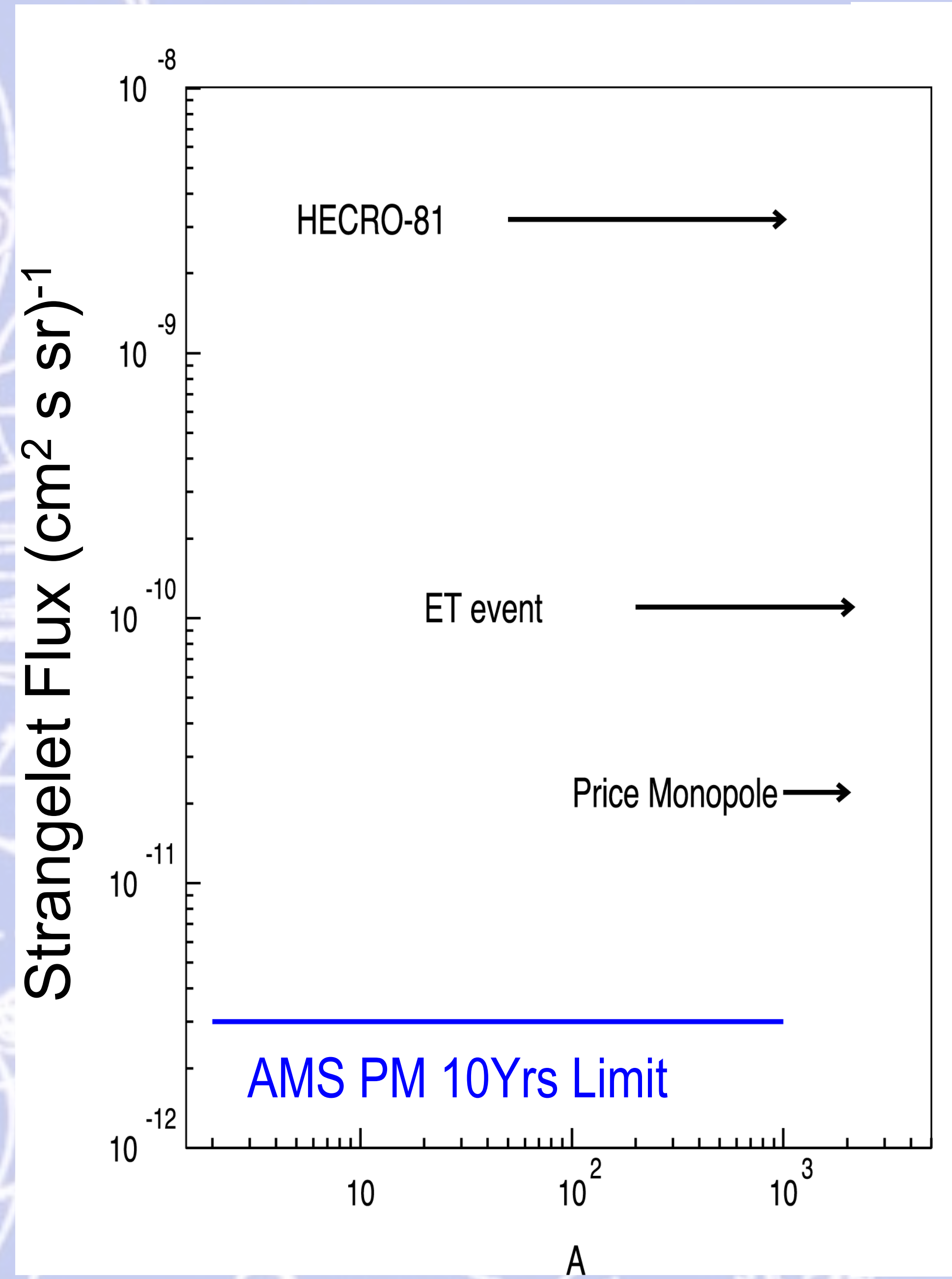
Rigidity = 4.31 ± 0.38 GV
Charge Z = 2
$\beta_1 = \beta_2 = 0.462 \pm 0.005$
Mass = 16.45 ± 0.15 GeV/c²
Z/A = 0.114 ± 0.01
Flux ($1.5 < E_K < 10$ GeV) = 5×10^{-5} $(m^2 sr\ sec)^{-1}$

Search for Strangelets

E. Witten, Phys. Rev. D,272-285 (1984)







Background probability < 10^{-3}

$\Phi_{strangelets} = 5x10^{-10}(cm^2 s\ sr)^{-1}$

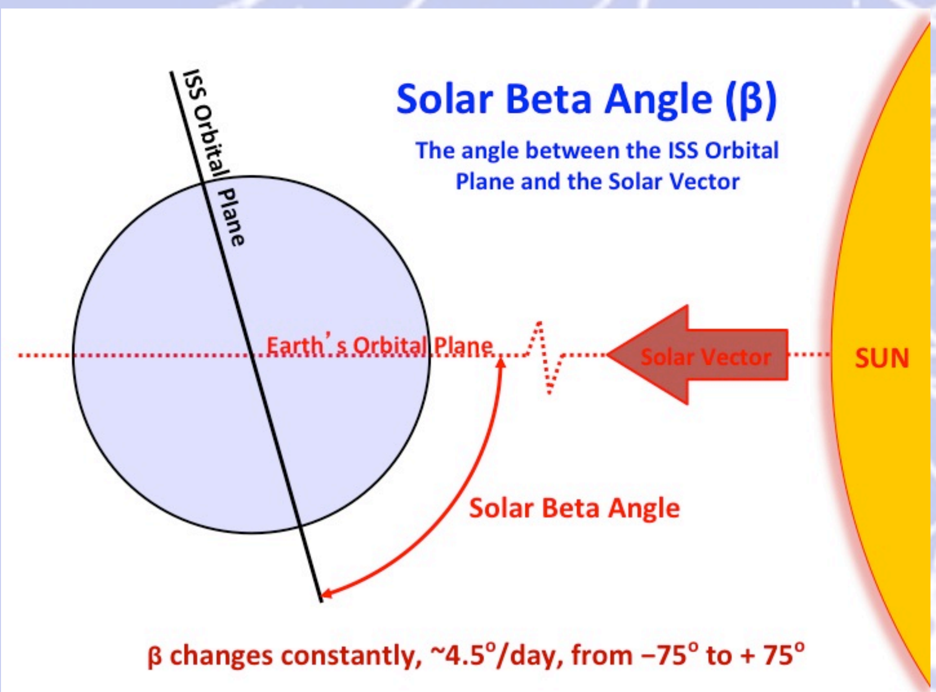
or ~30 in 1st year for AMS-02

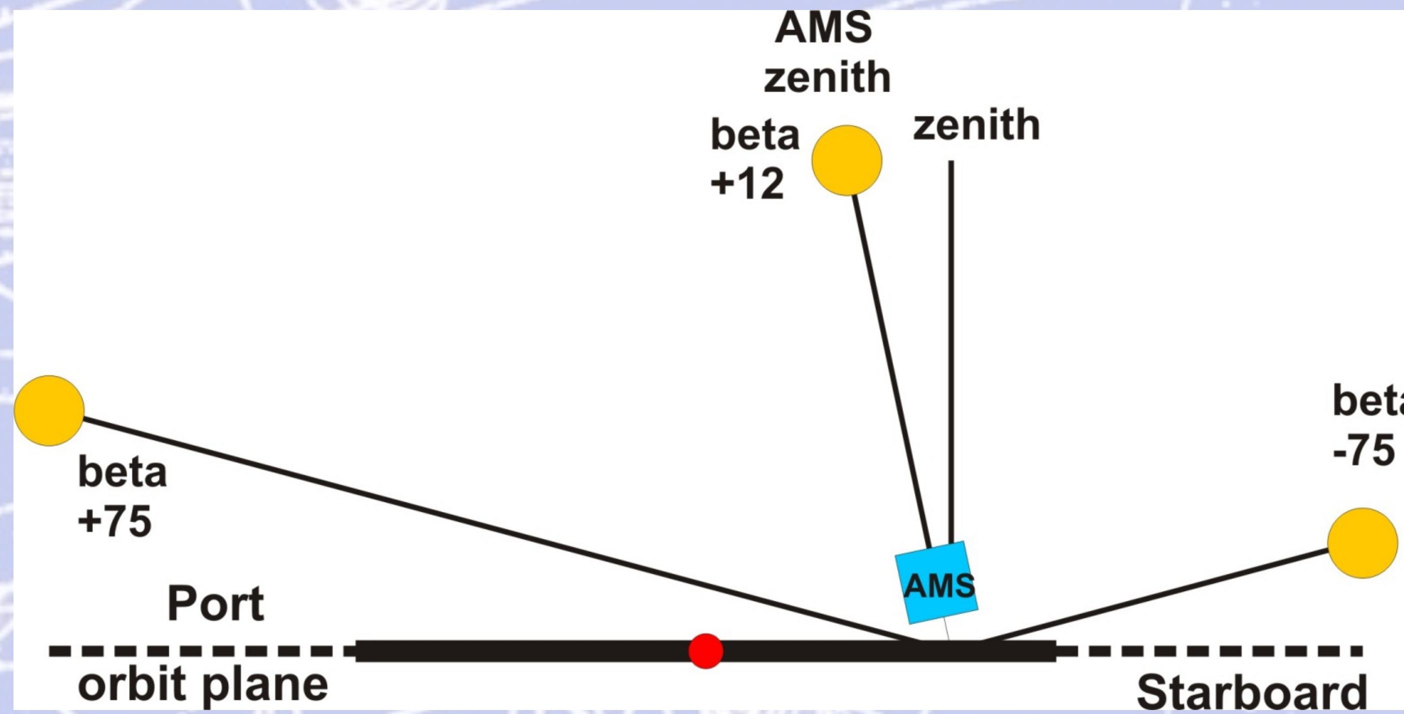
Appendice 8
(Condizioni termiche di AMS-02: angolo beta)

Thermal Control is the most challenging task in the operation of AMS

The thermal environment on ISS is constantly changing due to:

- **Solar Beta Angle (β)**
- **Position of the ISS Radiators and Solar Arrays**
- **ISS Attitude**





Over 1,100 temperature sensors and 298 heaters are monitored around the clock in the AMS POCC to assure components stay within thermal limits and avoid permanent damage.

Appendice 9

(Il tracciatore di AMS-02)

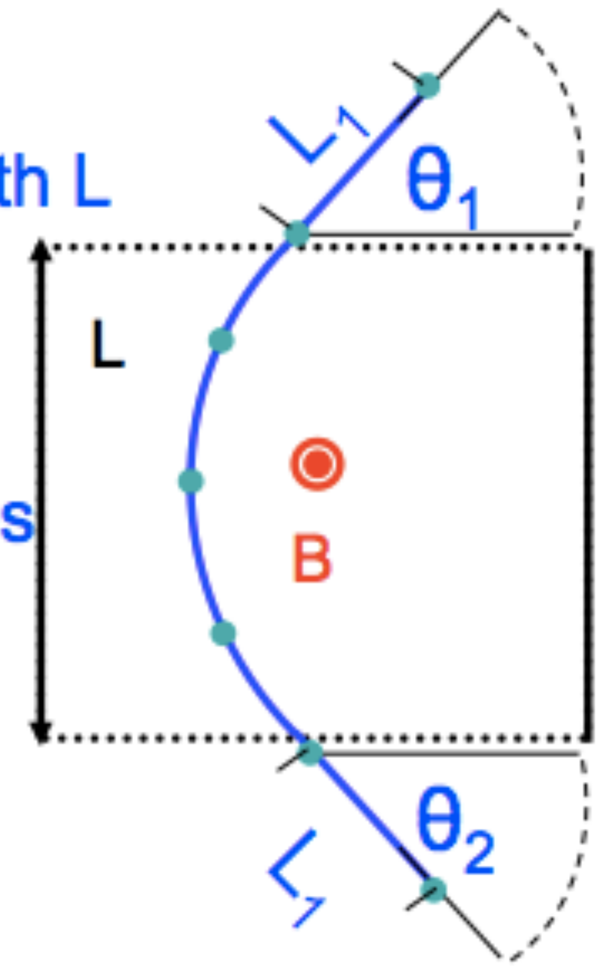
The momentum resolution ($\Delta p/p$) is the sum of two contributions:

1. Measurement inside the magnet with an effective length L

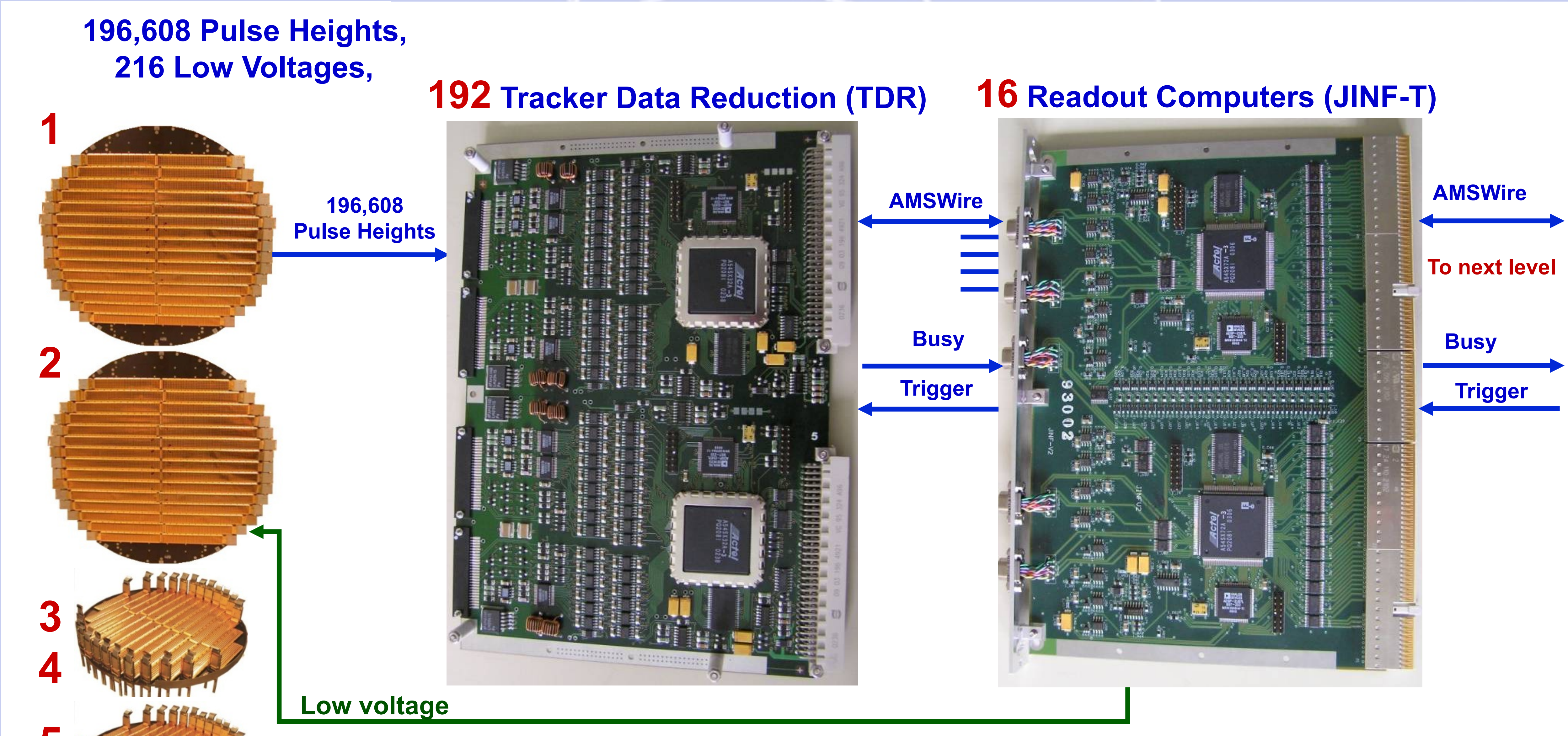
$$(Q/p)\cdot(\Delta p/p) \propto 1/BL^2$$

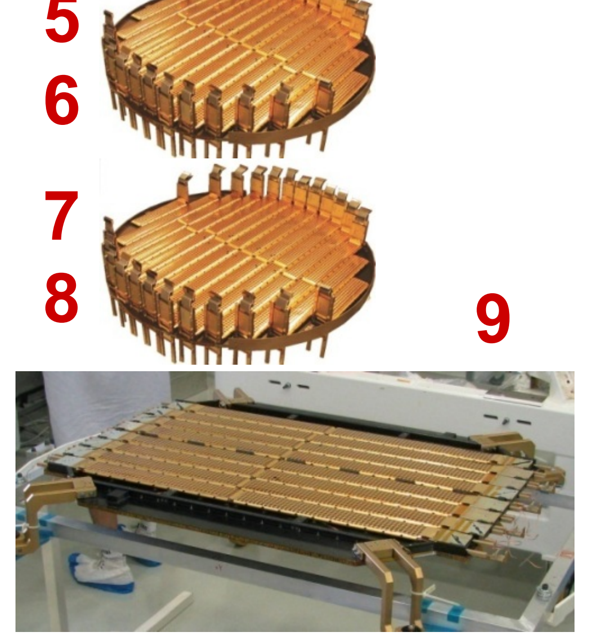
2. Measurement of the incident (θ_1) and exit (θ_2) angles which depend on the length L_1

$$(Q/p)\cdot(\Delta p/p) \propto 1/BLL_1$$



For both magnets, L ~ 80 cm,
but in the permanent magnet B is 5 times smaller
to maintain the same $\Delta p/p$ we increase L1 from ~15 cm (Superconducting Magnet) to ~125 cm (permanent magnet)





- **Analog to digital conversion**
  coordinate resolution of 10 µm
- **Data reduction:**
  Pedestal subtraction
  Noise suppression
  Cluster finding
- **Format, send to next level**

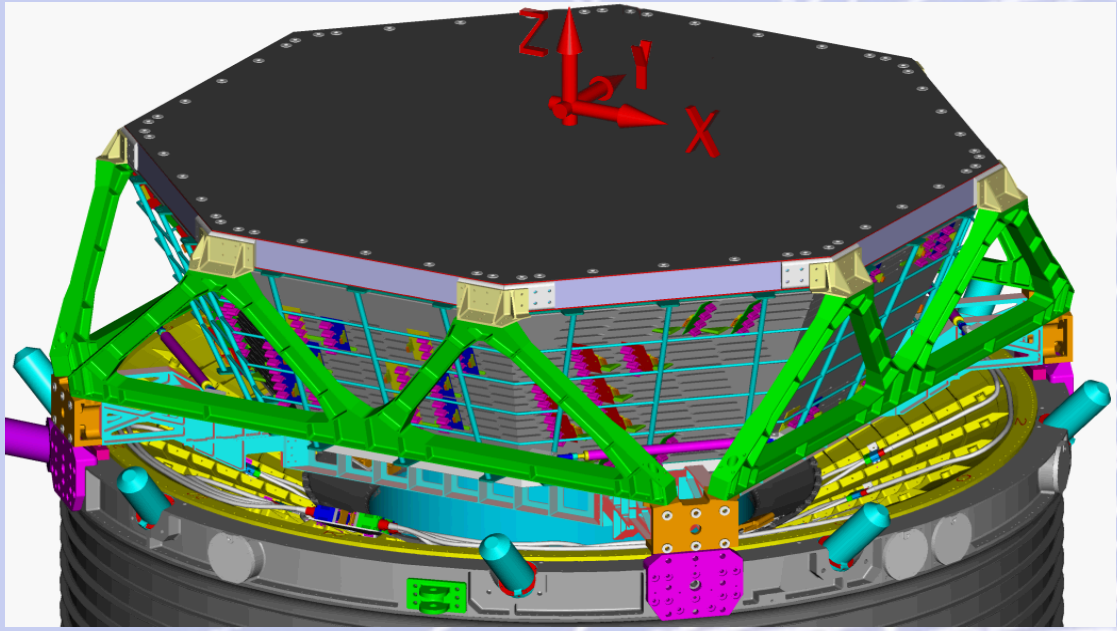
- **Collect data from TDR** (*)
- **Format, send to next level**
- **Control Low Voltages**
- **Combine Busy signals**
- **Distribute Trigger**
- **Distribute command to TDR**

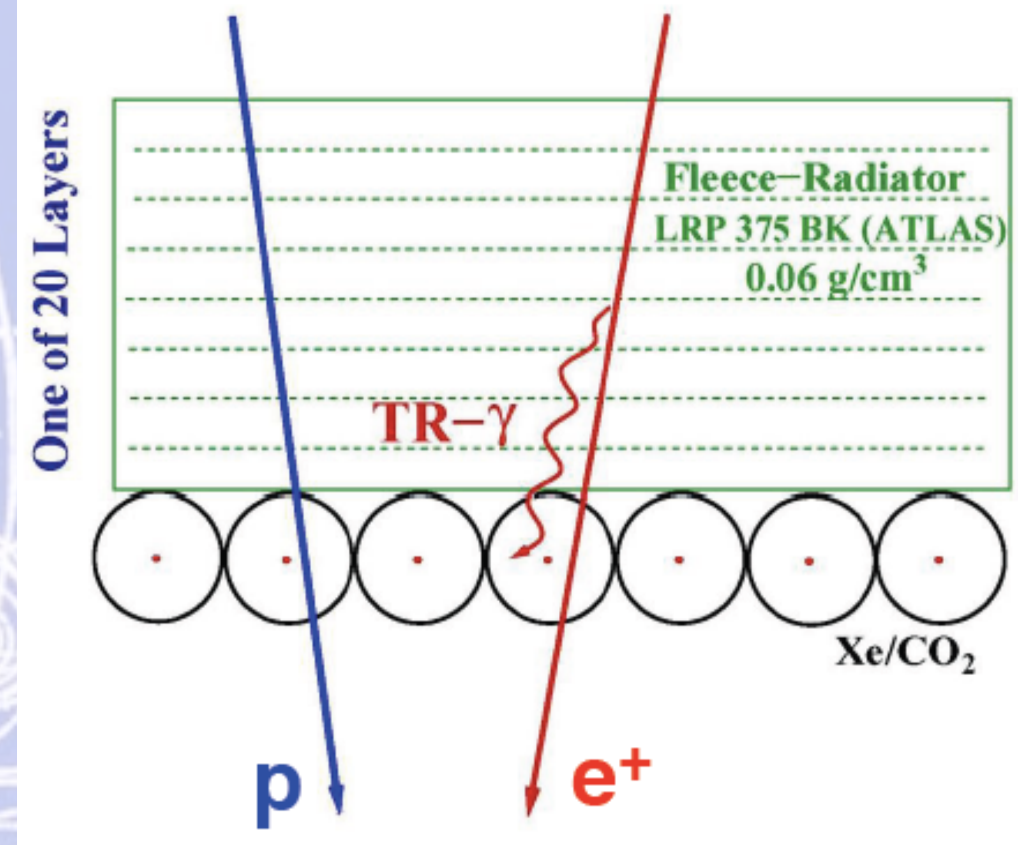
(*) Tracker Data Reduction

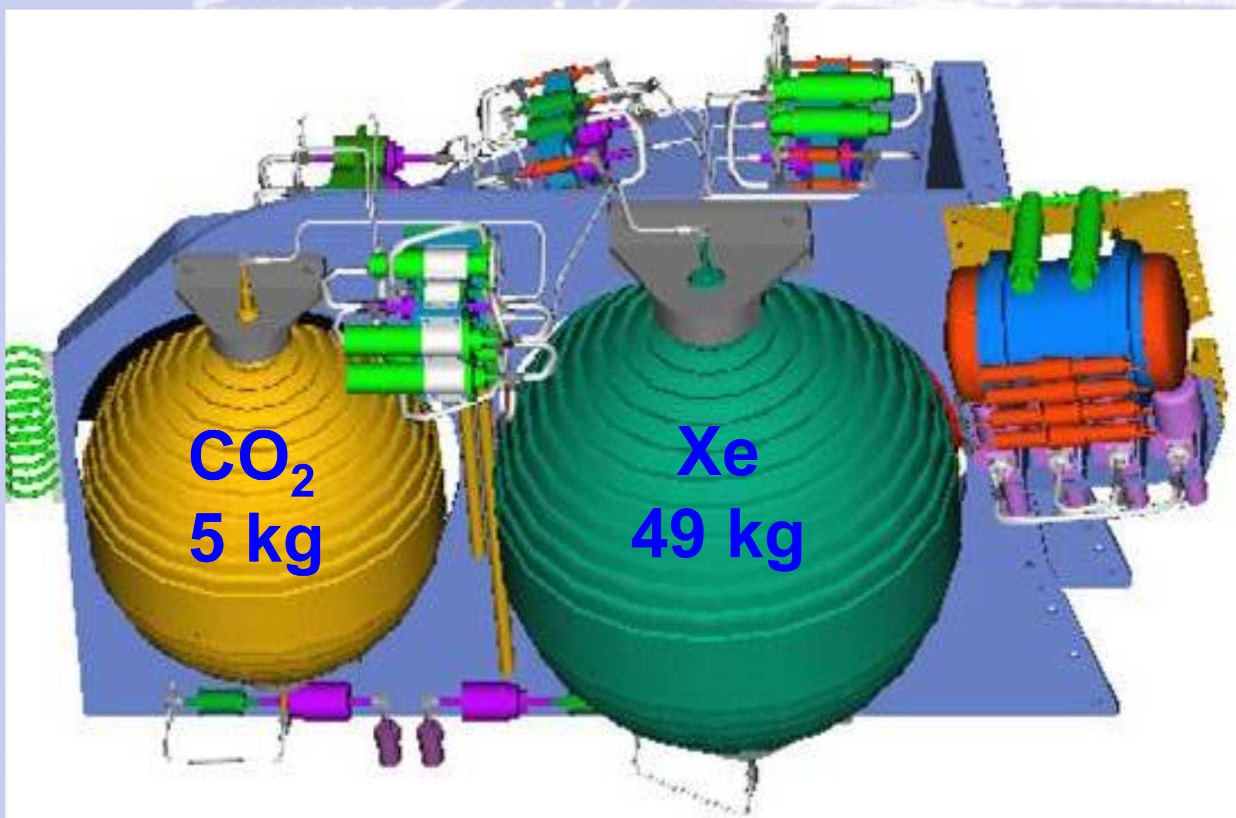
Appendice 10

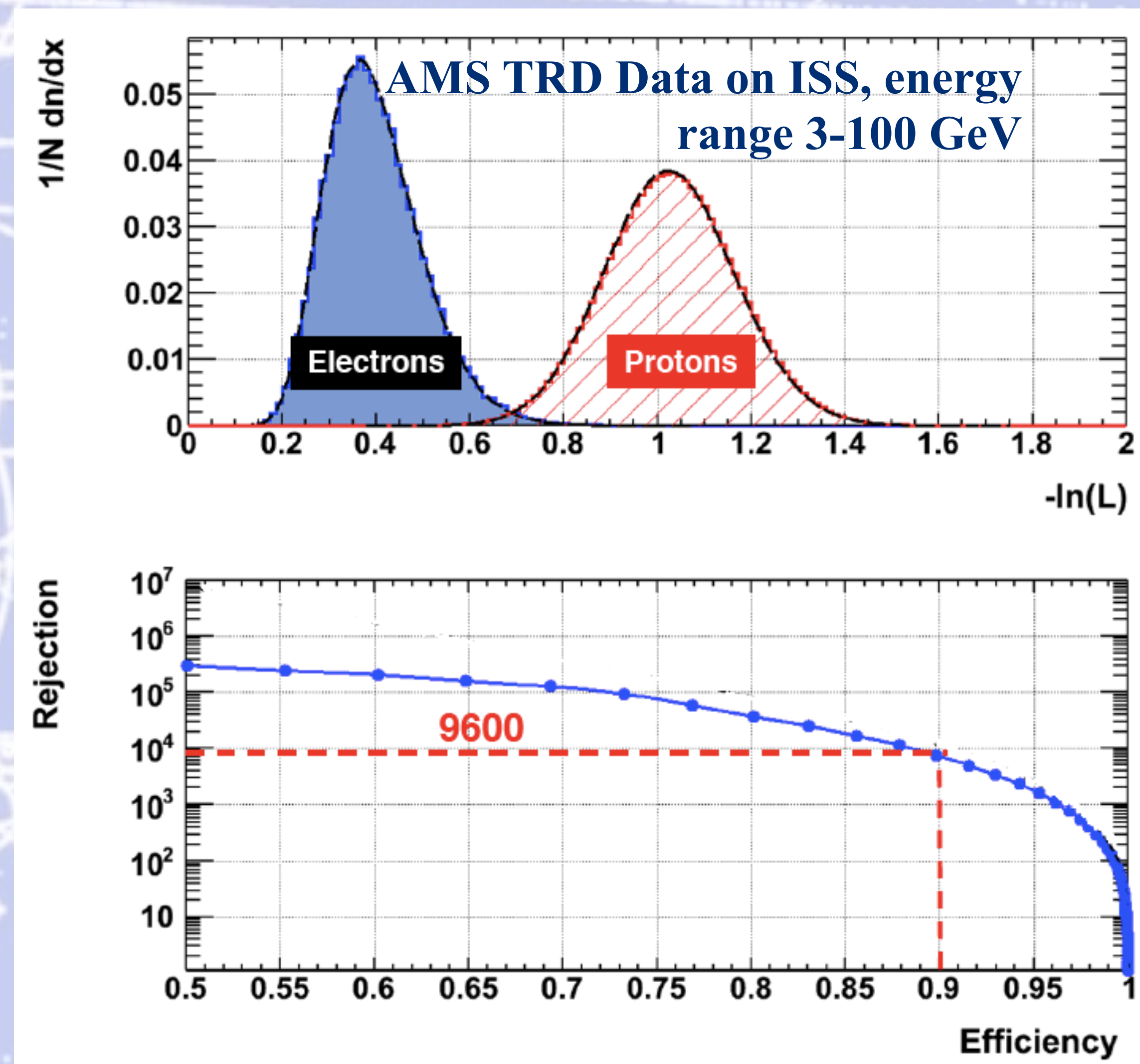
(Il TRD: Gas System)

Transition Radiation Detector (TRD)









Leakrate of 5 μg/s, caused by CO_2 diffusion, corresponds to a lifetime ~20 years in Space

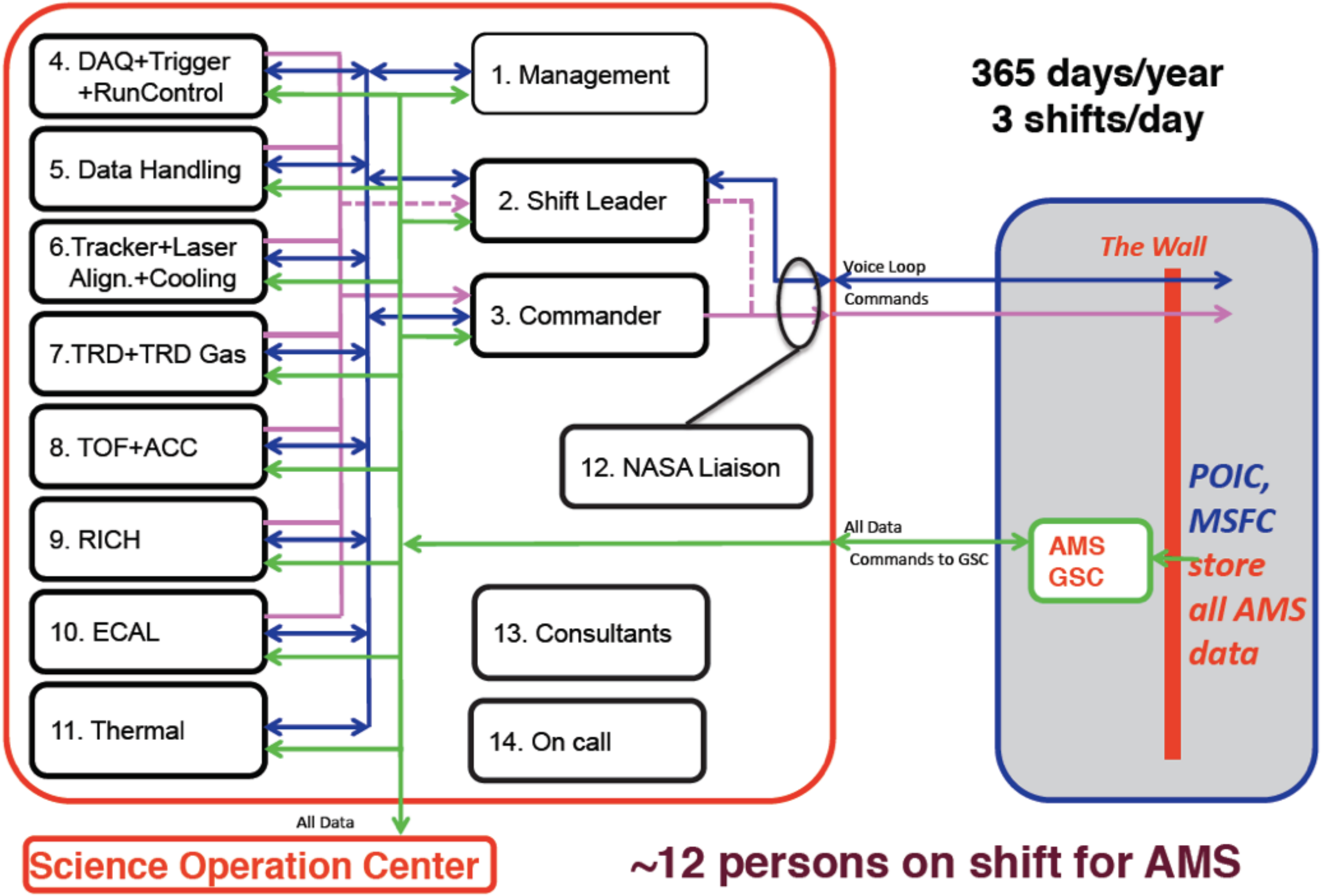
Appendice 11

(AMS DAQ)

AMS Data Acquisition System

To read out 300,000 channels at up to 2 KHz, we developed a large set of computers (650) which are programmable from the POCC and which readout all the different detectors with up to 400% redundancy. Hundreds of these computers are interconnected in a tree like structure with an 100 MBit/s serial link.

AMS Payload Operation and Control Center for ISS



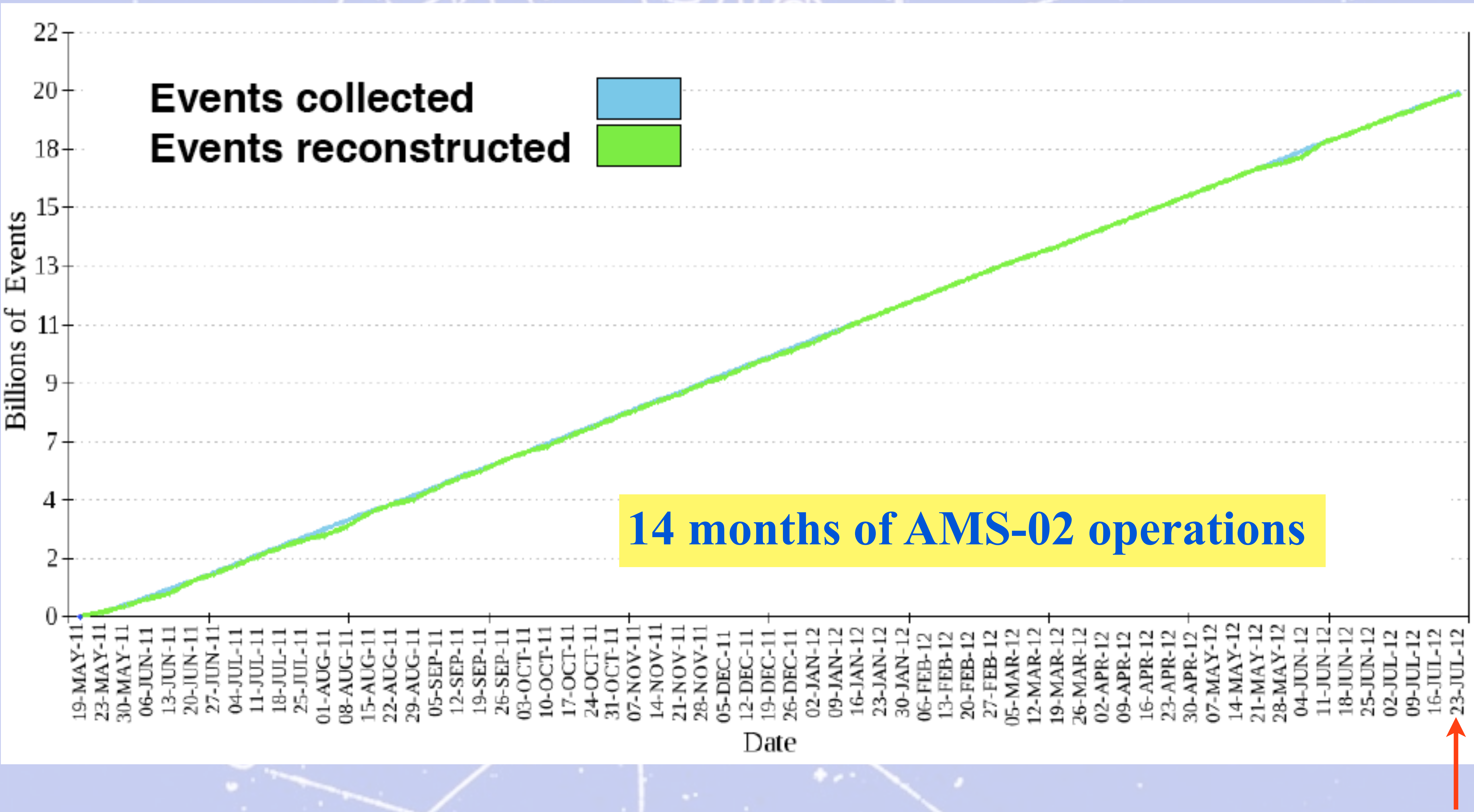
365 days/year
3 shifts/day

~12 persons on shift for AMS

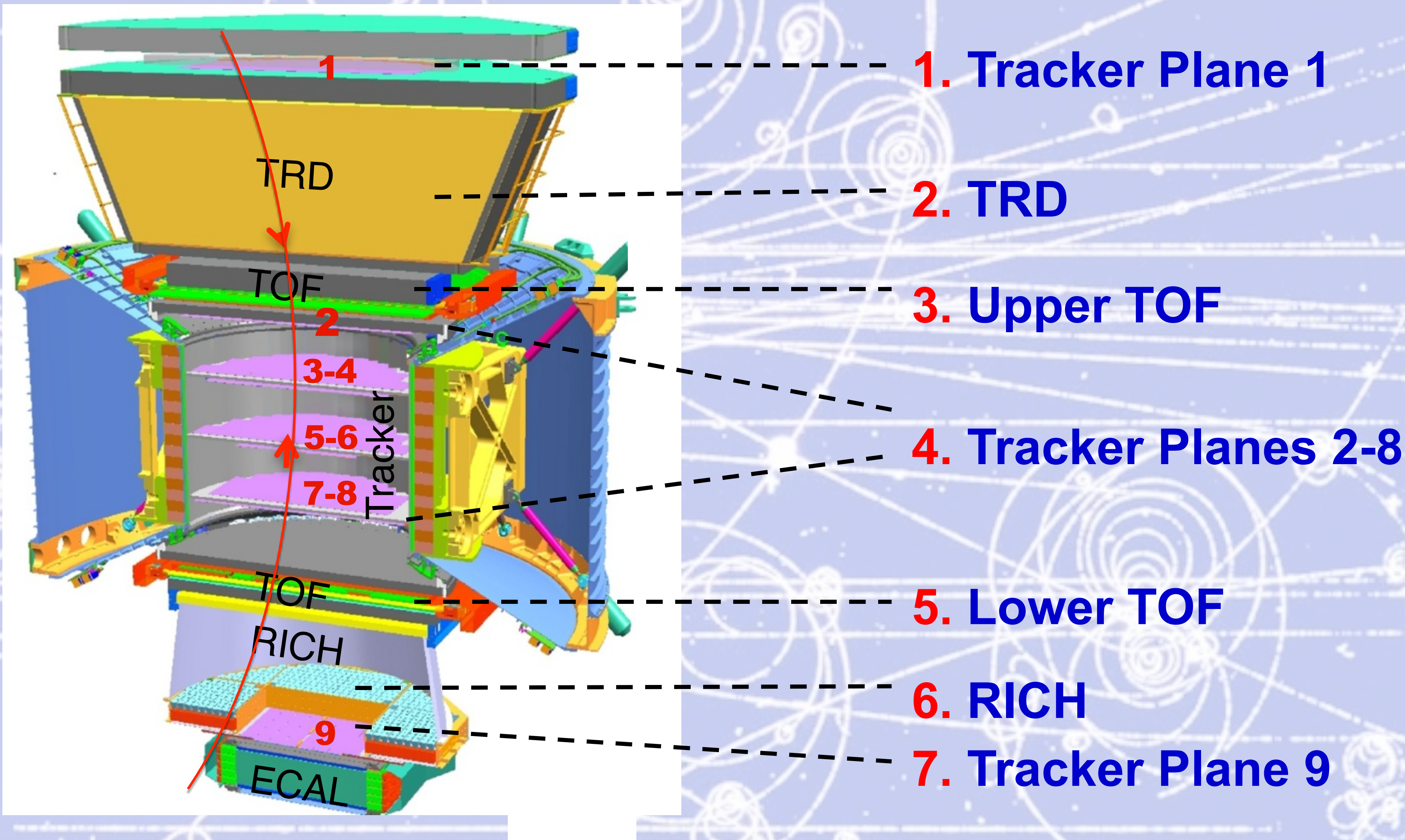
Appendice 12

(AMS-02 performance)

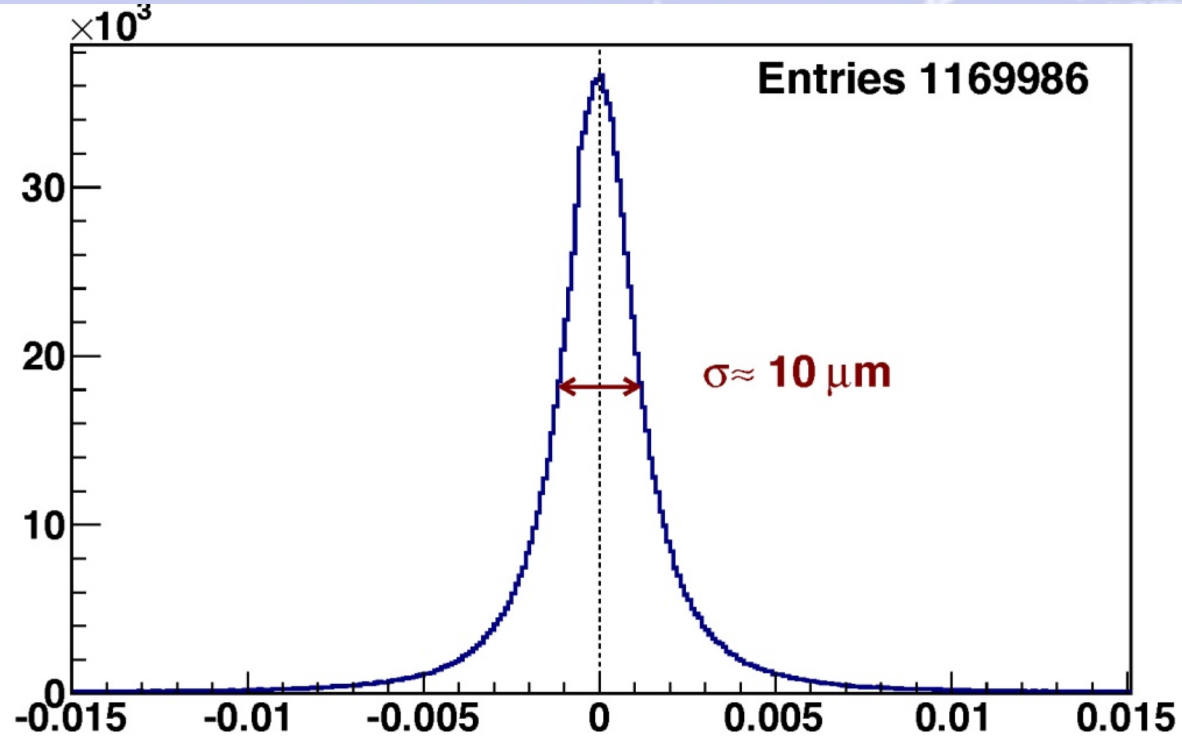
AMS-02 collected over 20 billion events in 14 months operation on ISS



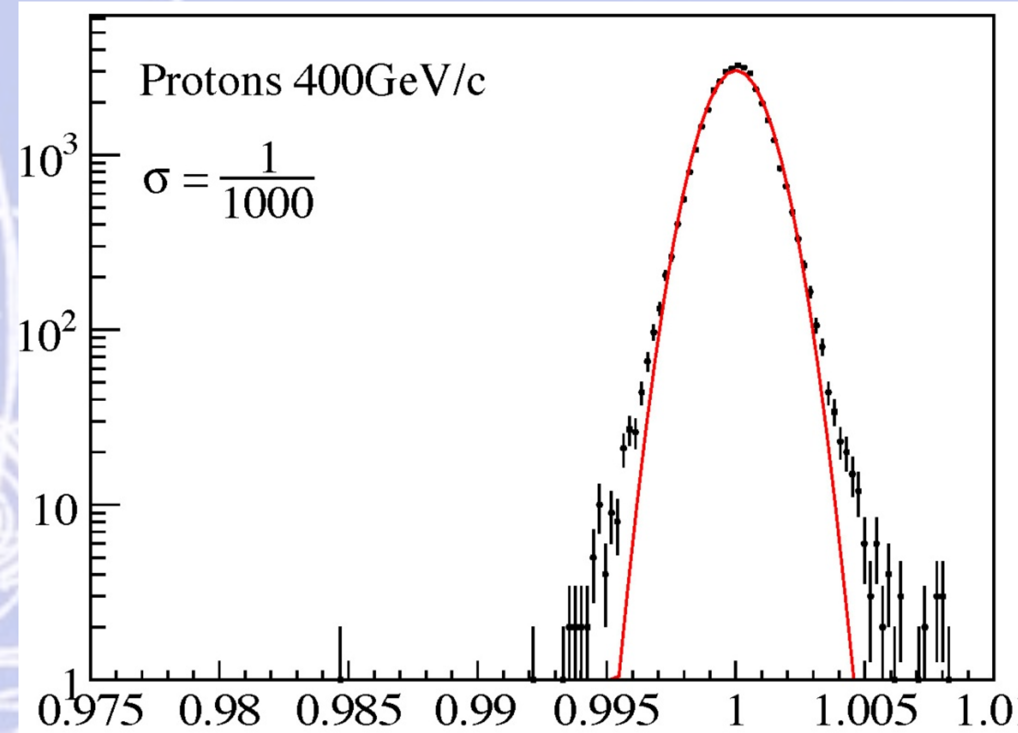
Multiple independent Measurements of the Charge (|Z|)



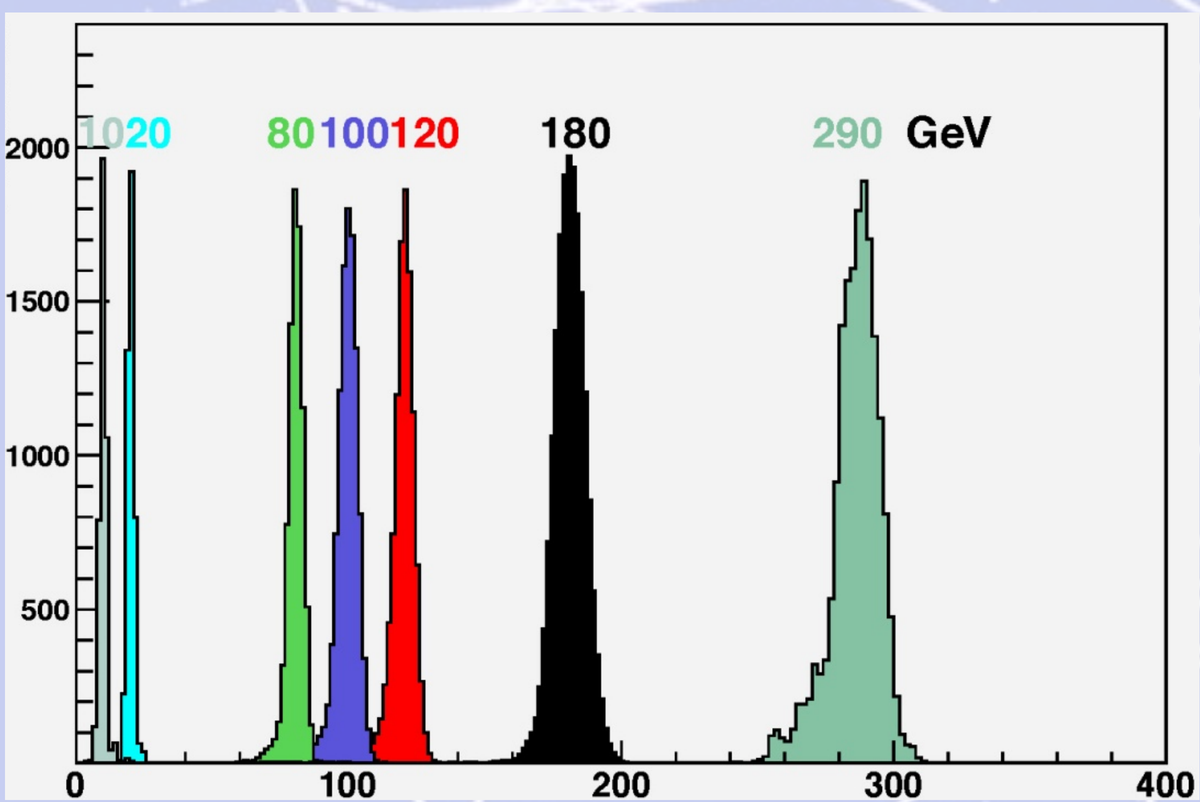
Test Beam Results at CERN 2010 (8-20 Aug)

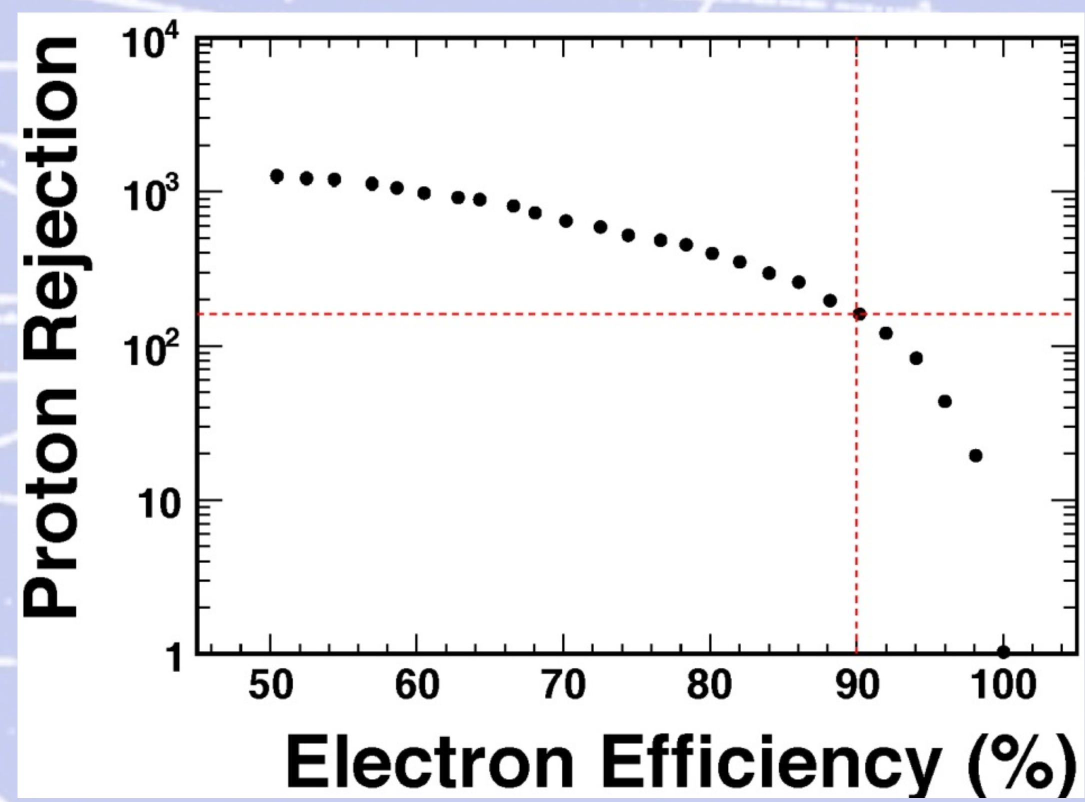


Bending Plane Residual (cm)



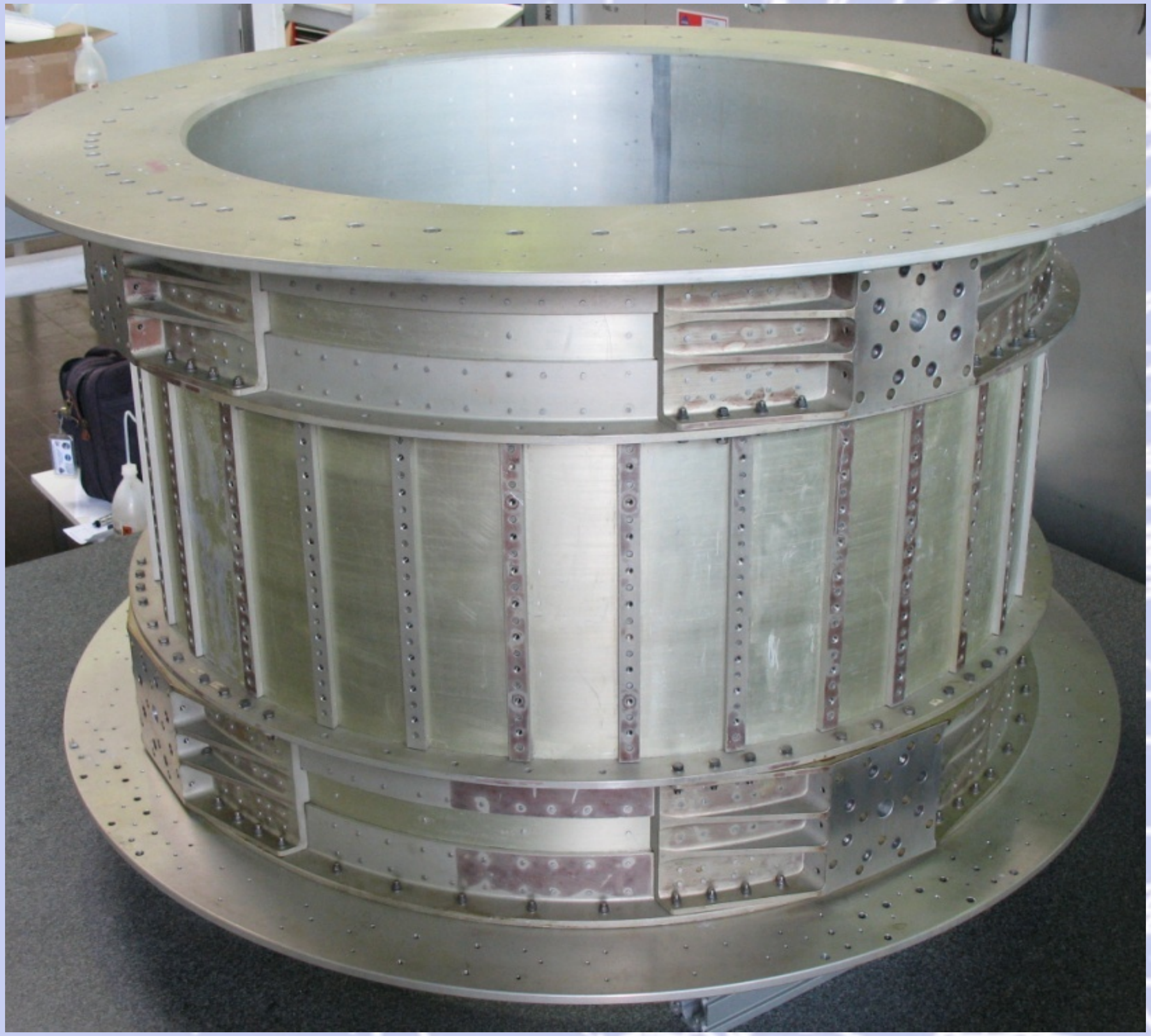
Reconstructed Velocity

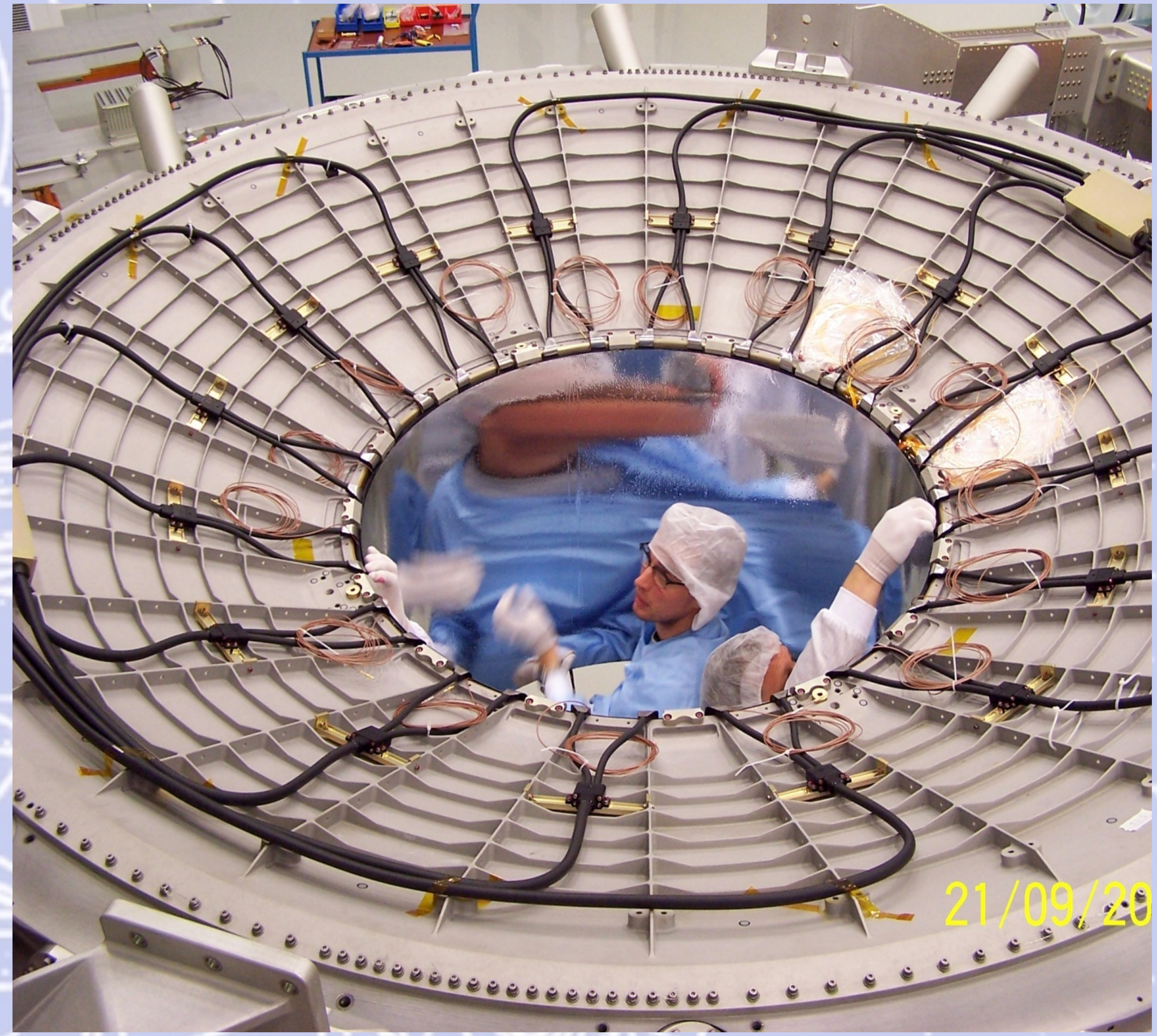




Measured combined rejection power at 400 GeV: $e^+/p = 10^{-6}$

The Magnet and the VETO System reject random Cosmic Rays





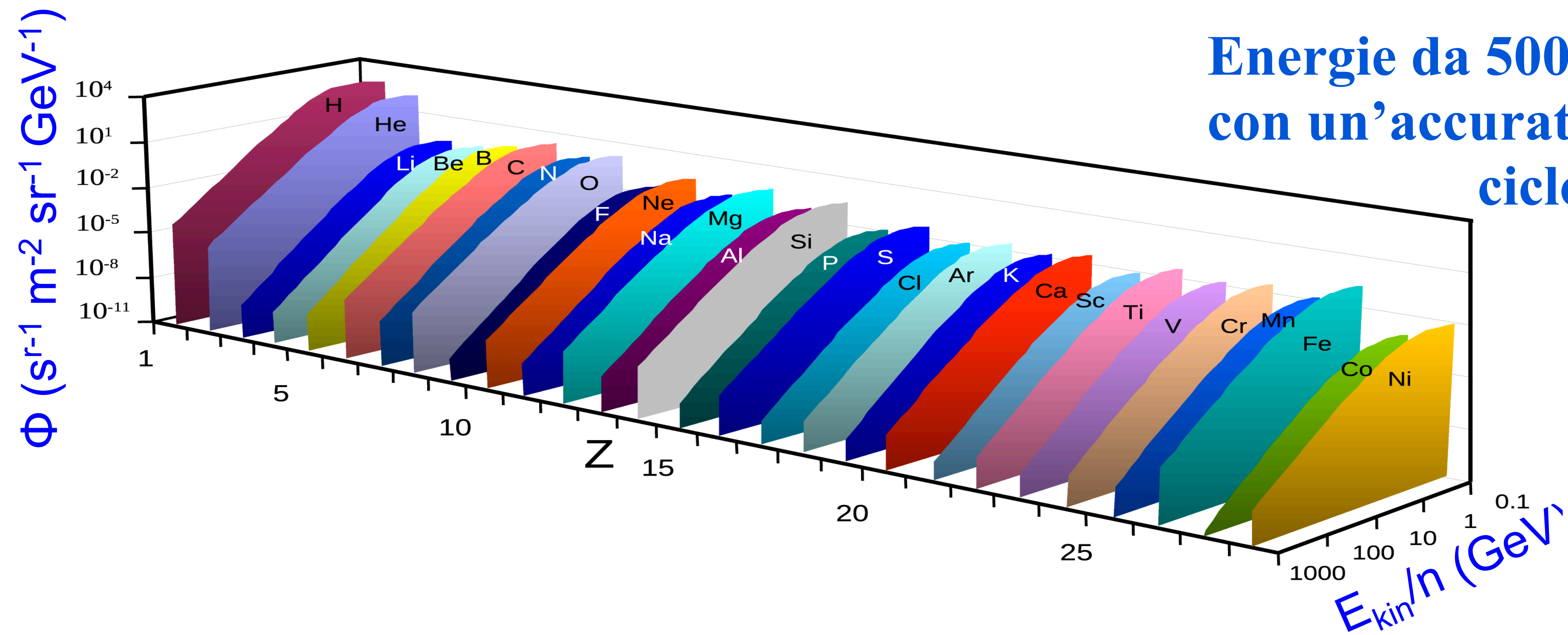
In 12 years the field has remained the same to < 1% (from 1997 to 2010)

Measured VETO (ACC) efficiency better than 0.99999

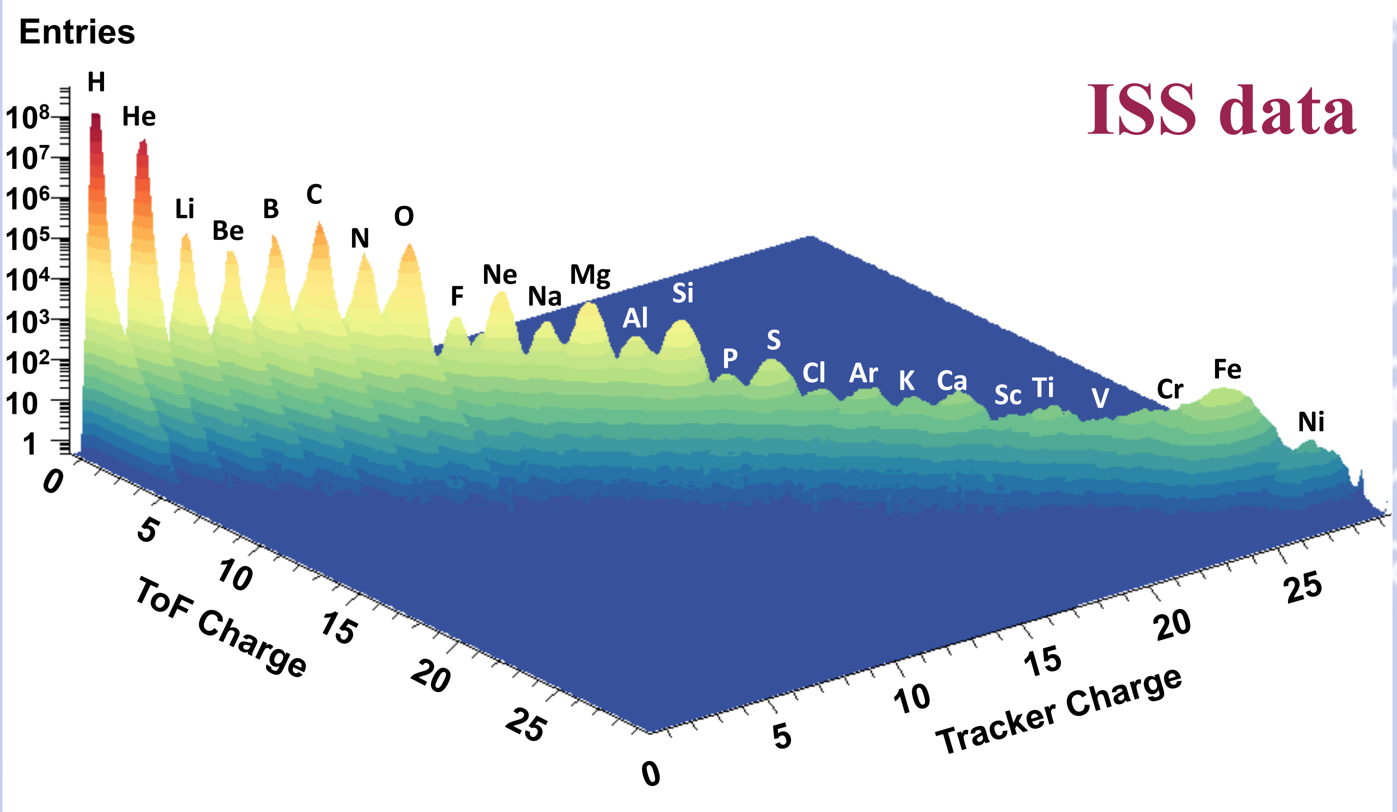
Appendice 13

(Risultati AMS-02 da maggio 2011 a settembre 2014)

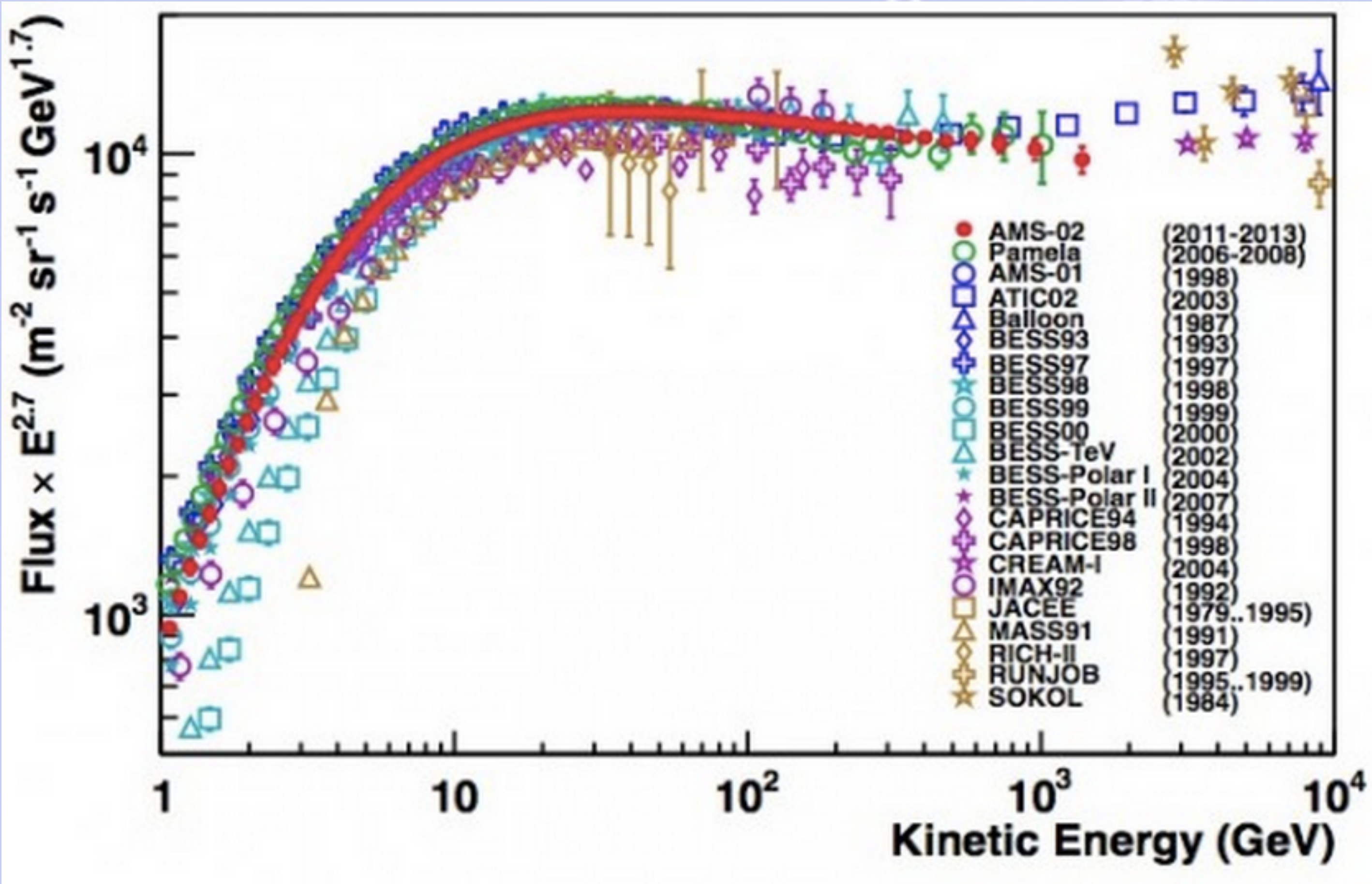
La fisica di AMS-02: misure di abbondanza nucleare



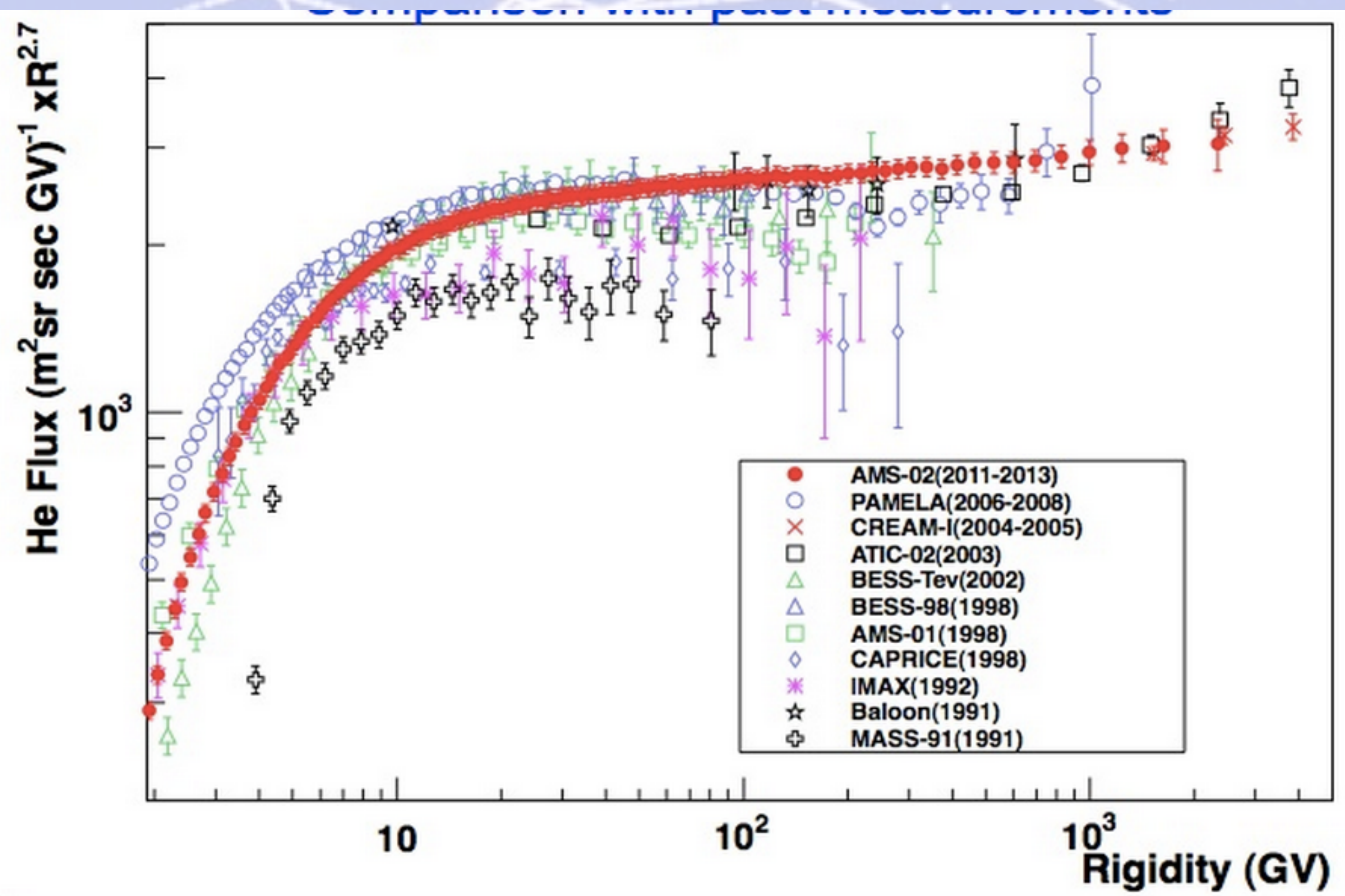
Energie da 500 MeV a 2 TeV con un'accuratezza dell'1% sul ciclo solare (11 anni).



Questi spettri forniscono dati sperimentali necessari per calcolare il "background" nella ricerca della Materia Oscura, i.e., $p + C \longrightarrow e^+, p, \ldots$..



Flusso di protoni
(ICRC 2013)



Flusso dell'elio
(ICRC 2013)

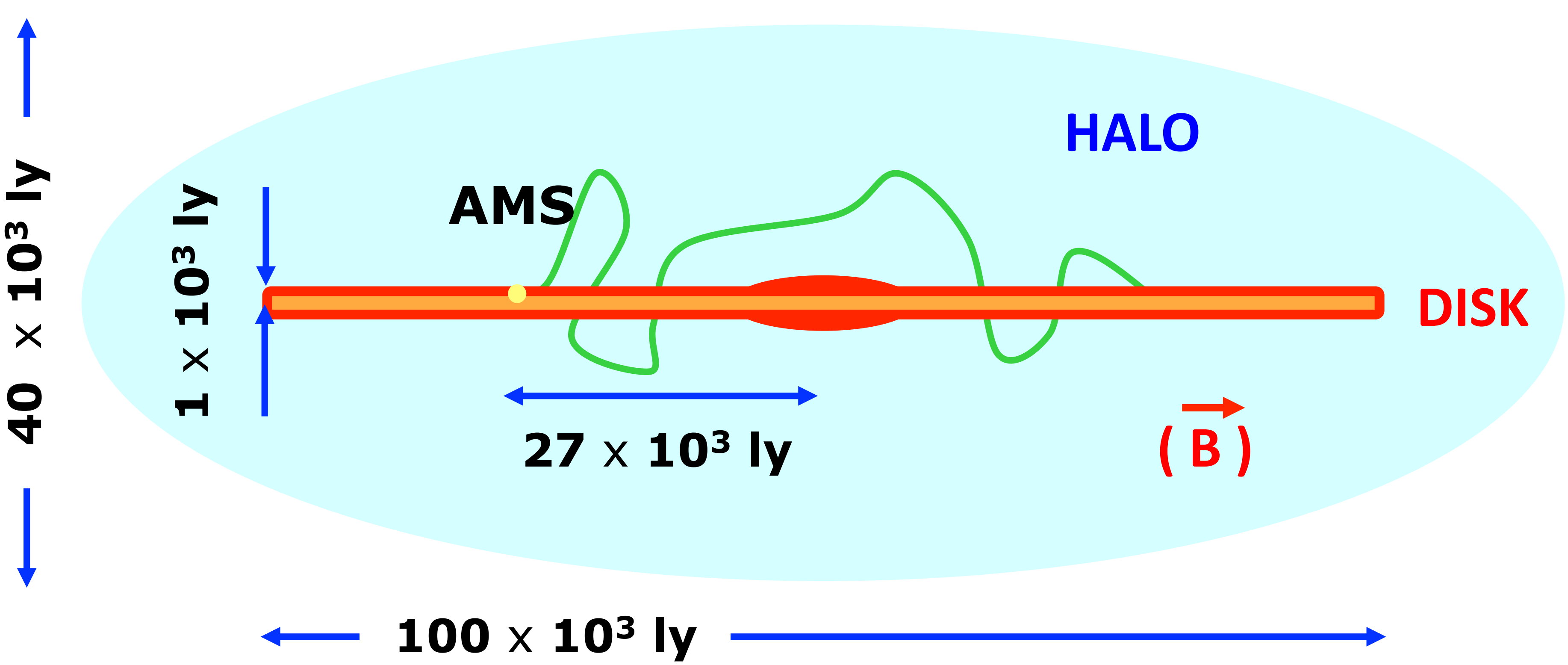
La fisica di AMS-02: rapporto Boro/Carbonio

Misure precise degli spettri di energia del B/C
forniscono informazioni sulle interazioni e la propagazione dei CR

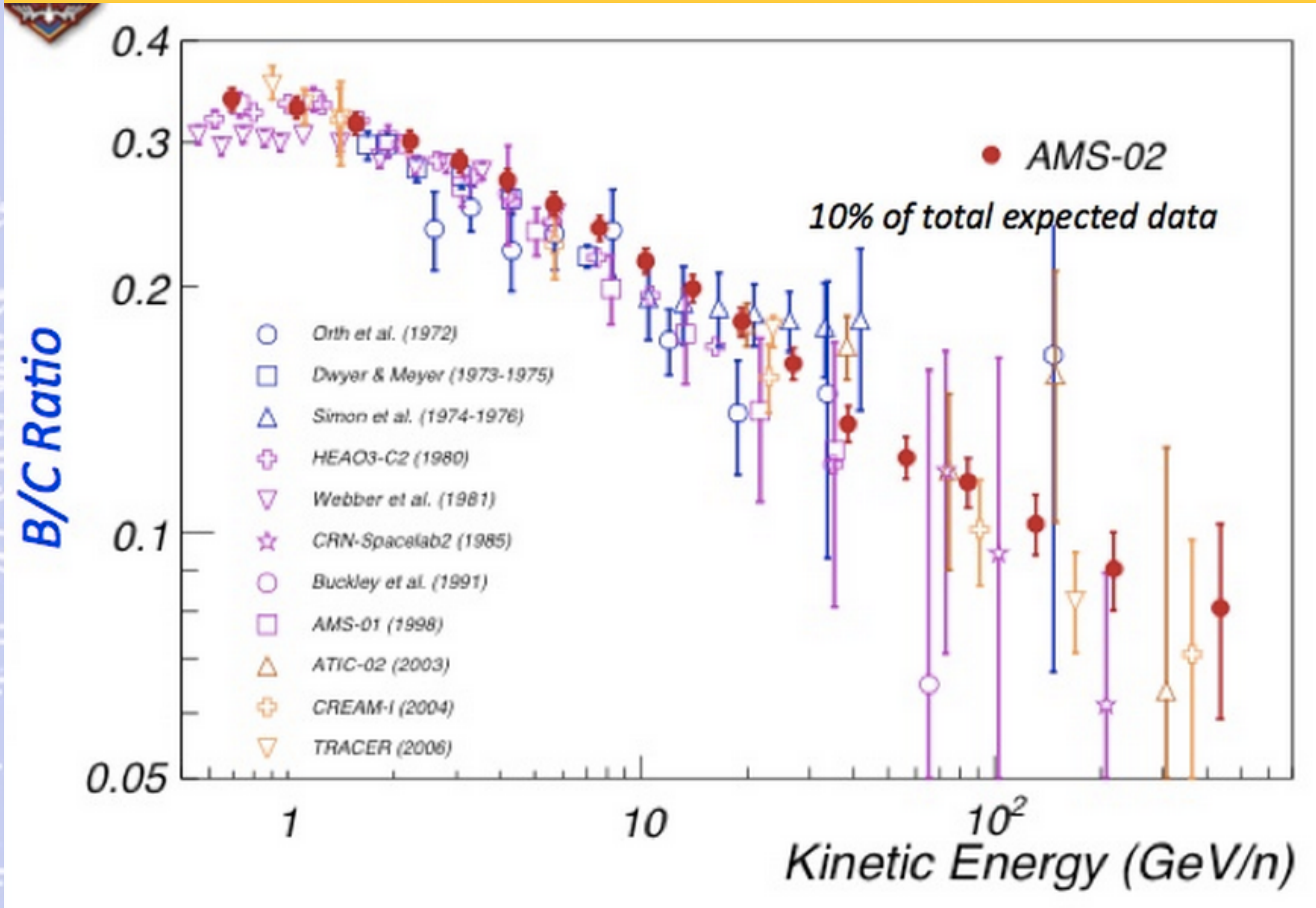
Interazioni con il Mezzo Interstellare:
C + (p,He) → B + ...

Diffusione
Convezione
Ri-accelerazione

Interactioni con il Mezzo Interstellare (ISM):
- **Frammentazione**
- **Secondari**
- **Perdite energetiche**

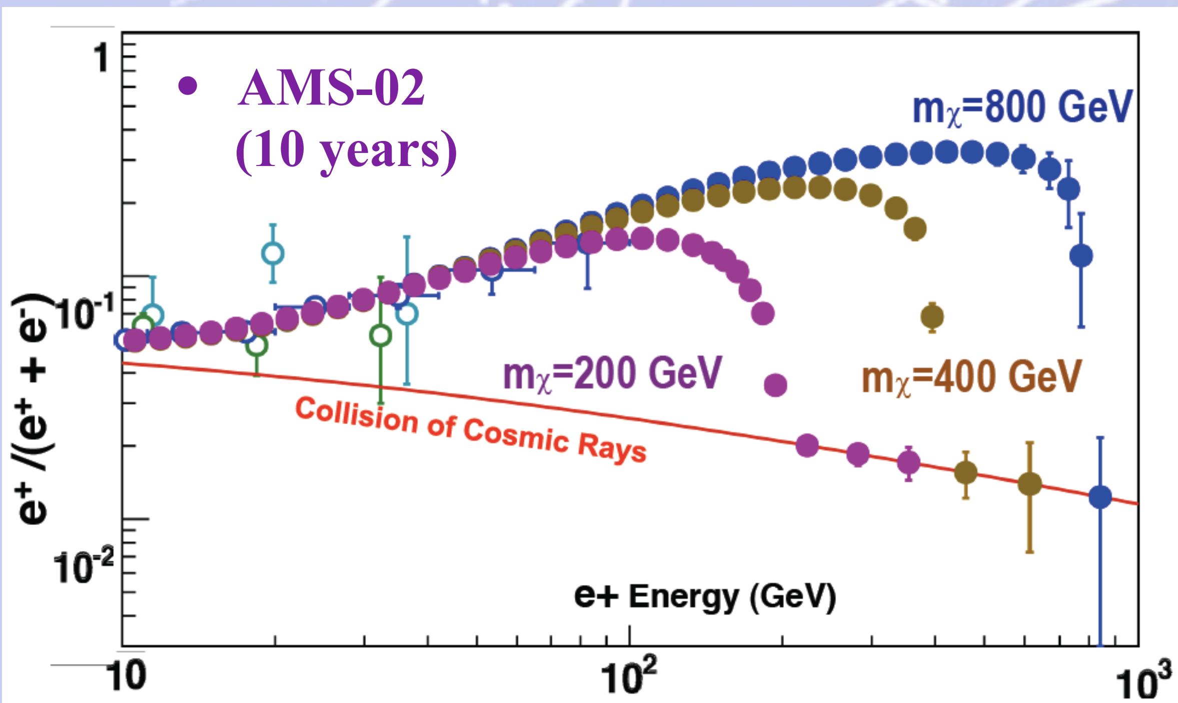


Rapporto Boro/Carbonio (ICRC 2013)

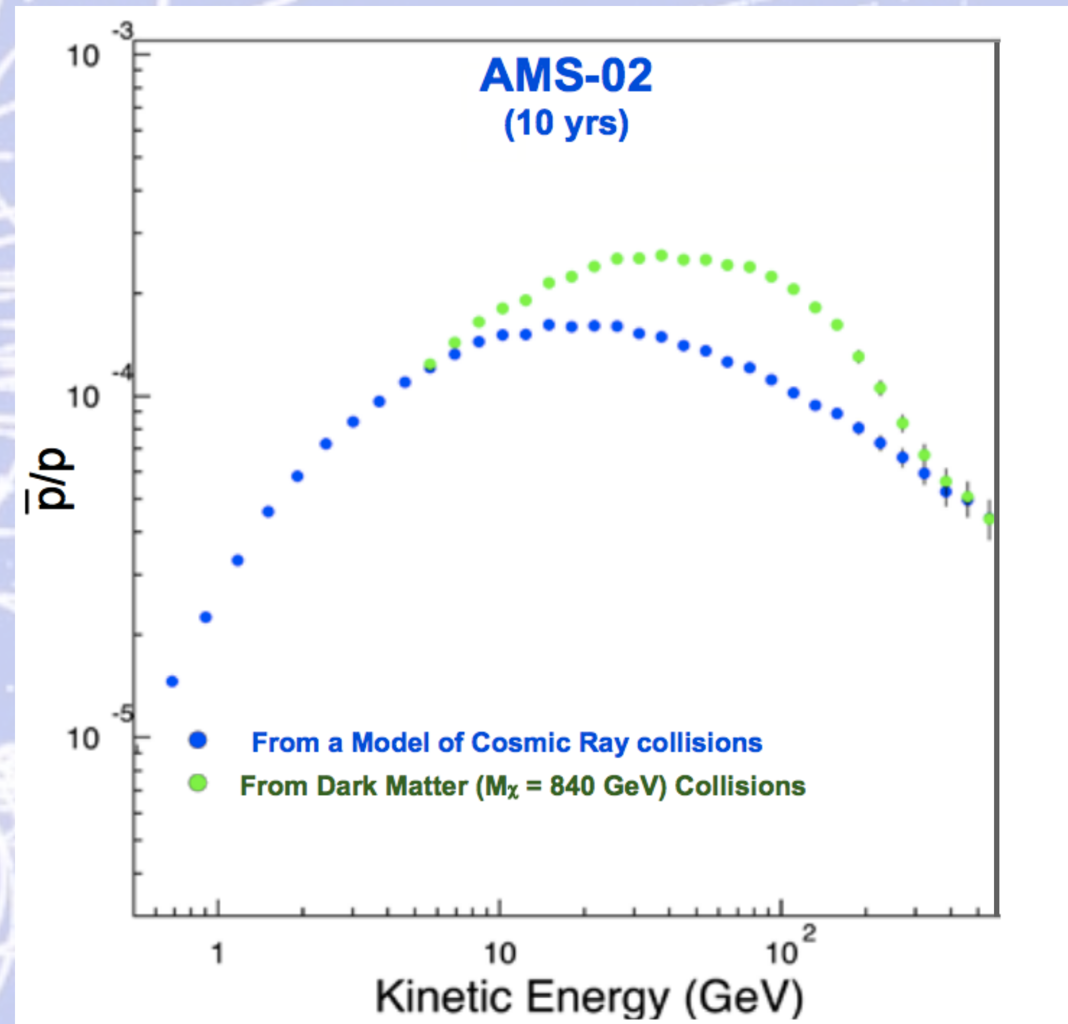


La fisica di AMS-02: ricerca indiretta della Materia Oscura

AMS-02 ha la capacita' di studiare l'annichilazione del Neutralino (candidato della Materia Oscura) usando simultaneamente quattro diversi stati finali di particelle: positroni, anti-protoni, anti-deuteroni and fotoni.

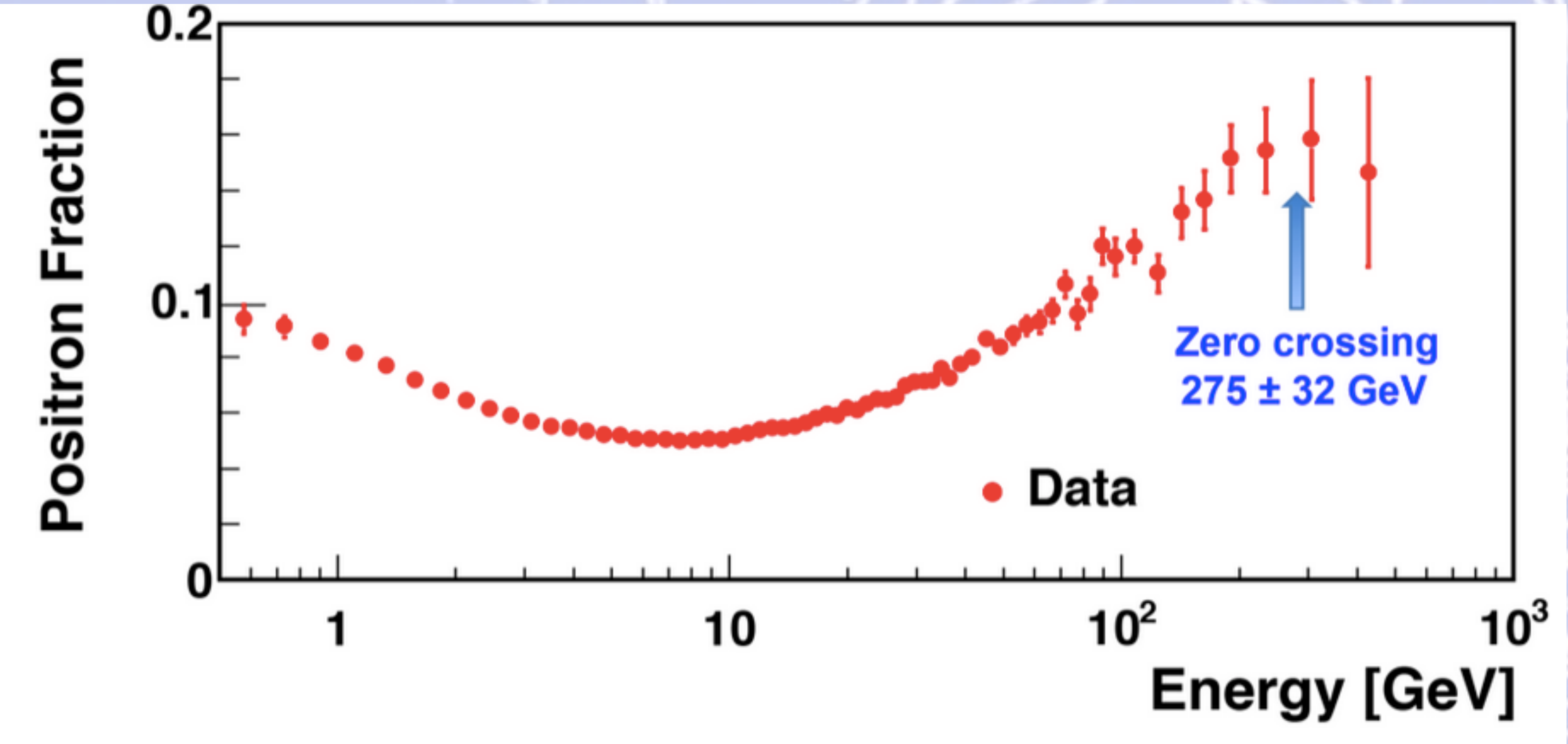


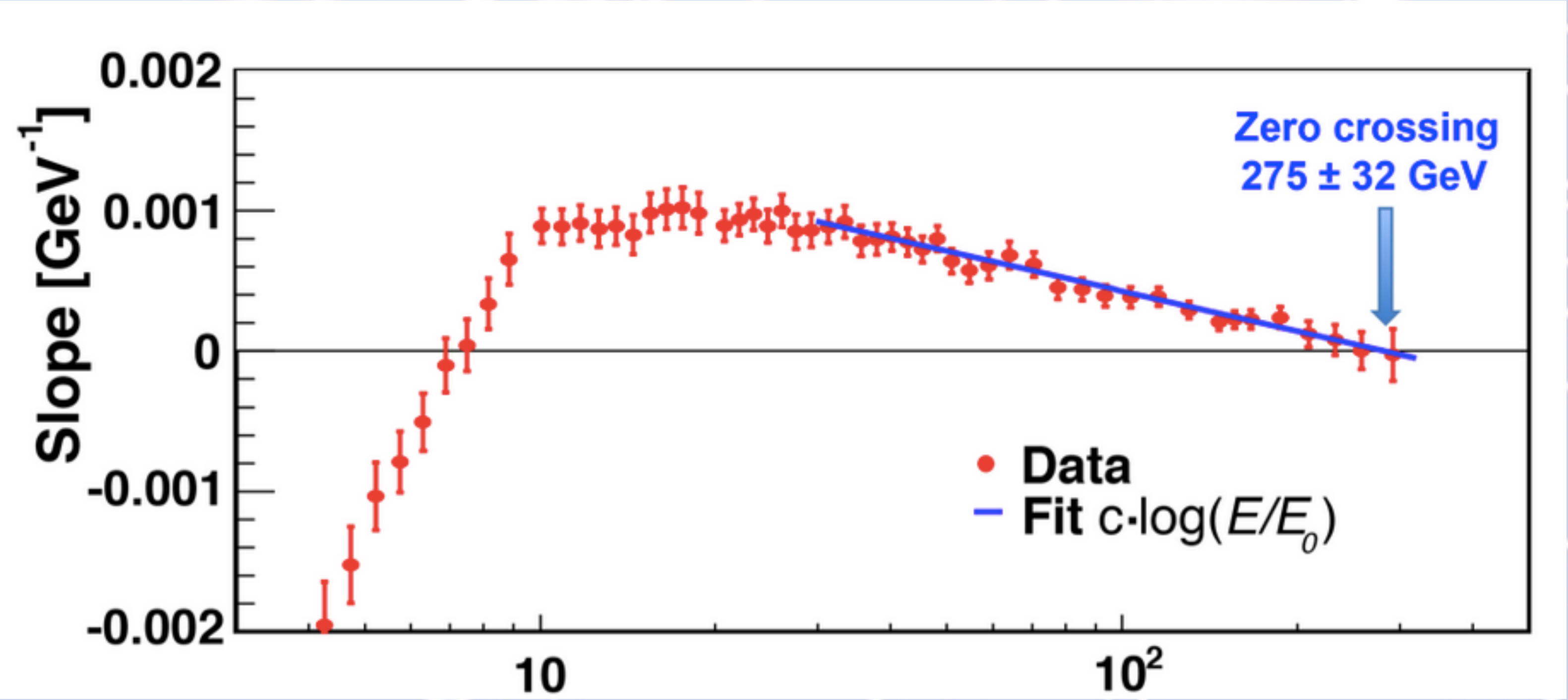
Segnale aspettato per la Materia Oscura da AMS-02 relativo alla misura della frazione del flusso di positroni e considerando diverse ipotesi della massa del Neutralino.



Segnale aspettato per la Materia Oscura da AMS-02 relativo alla misura della frazione del flusso di antiprotoni nell'ipotesi di massa del Neutralino $M\chi$ = 840 GeV .

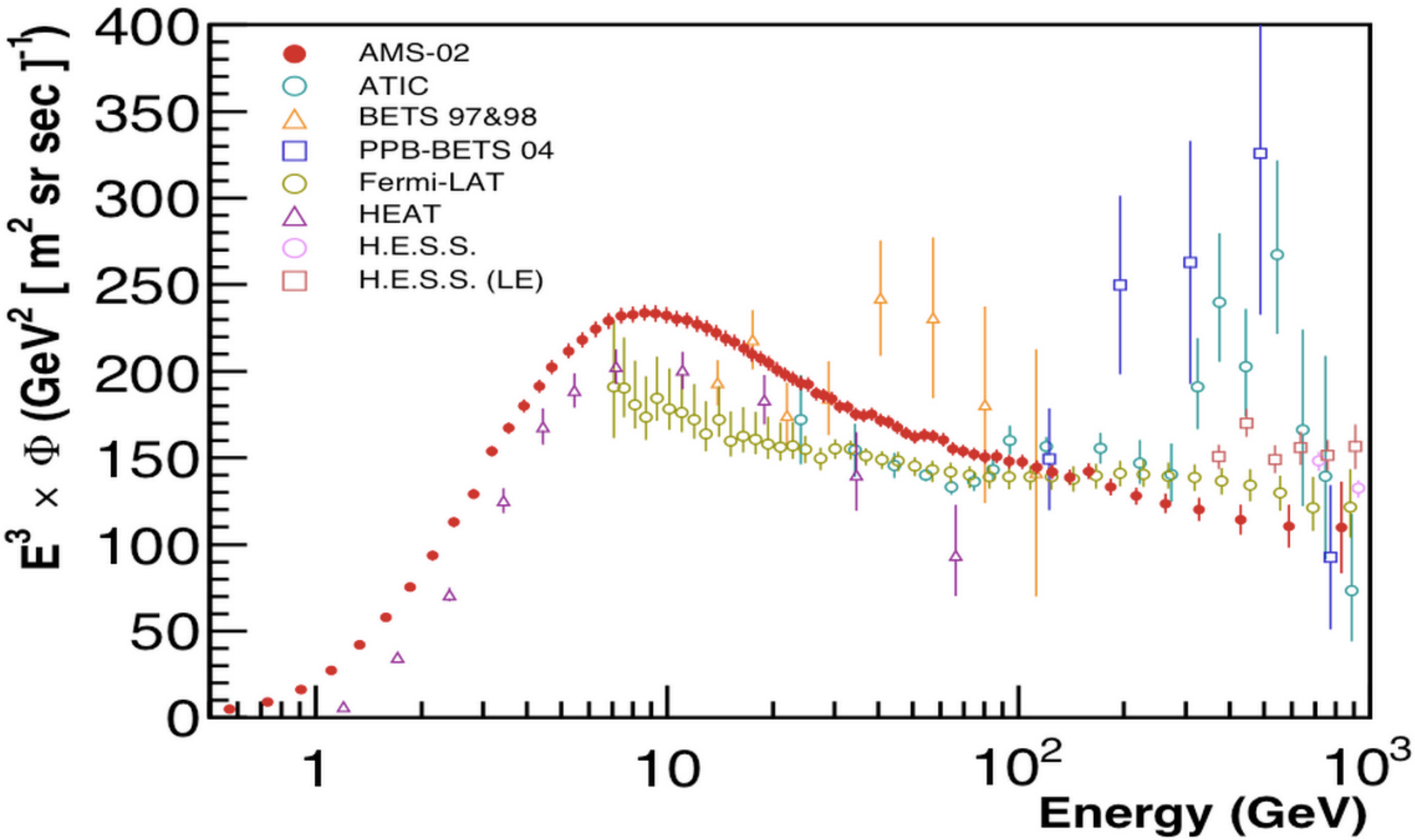
La fisica di AMS-02: ricerca indiretta della Materia Oscura

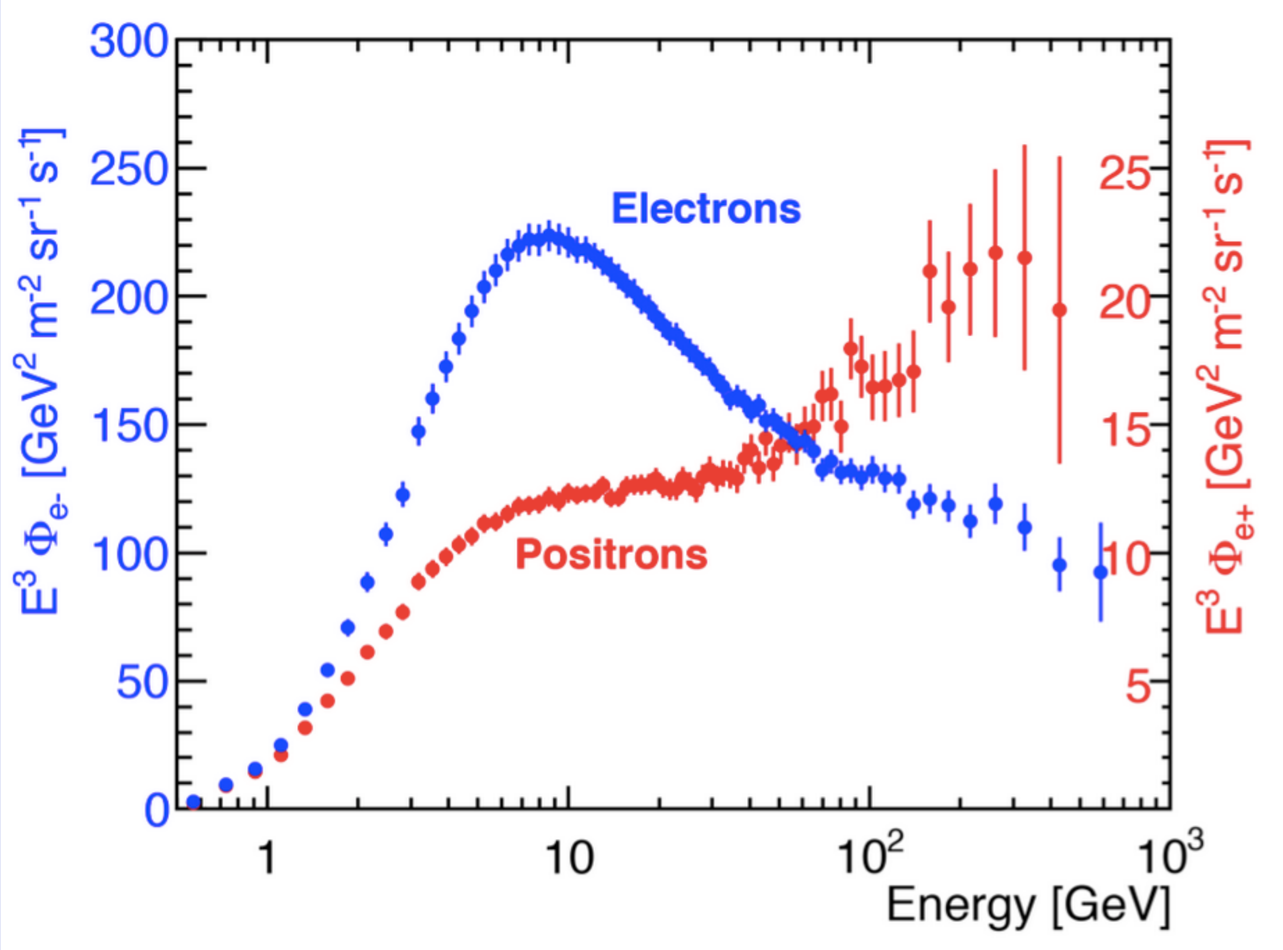




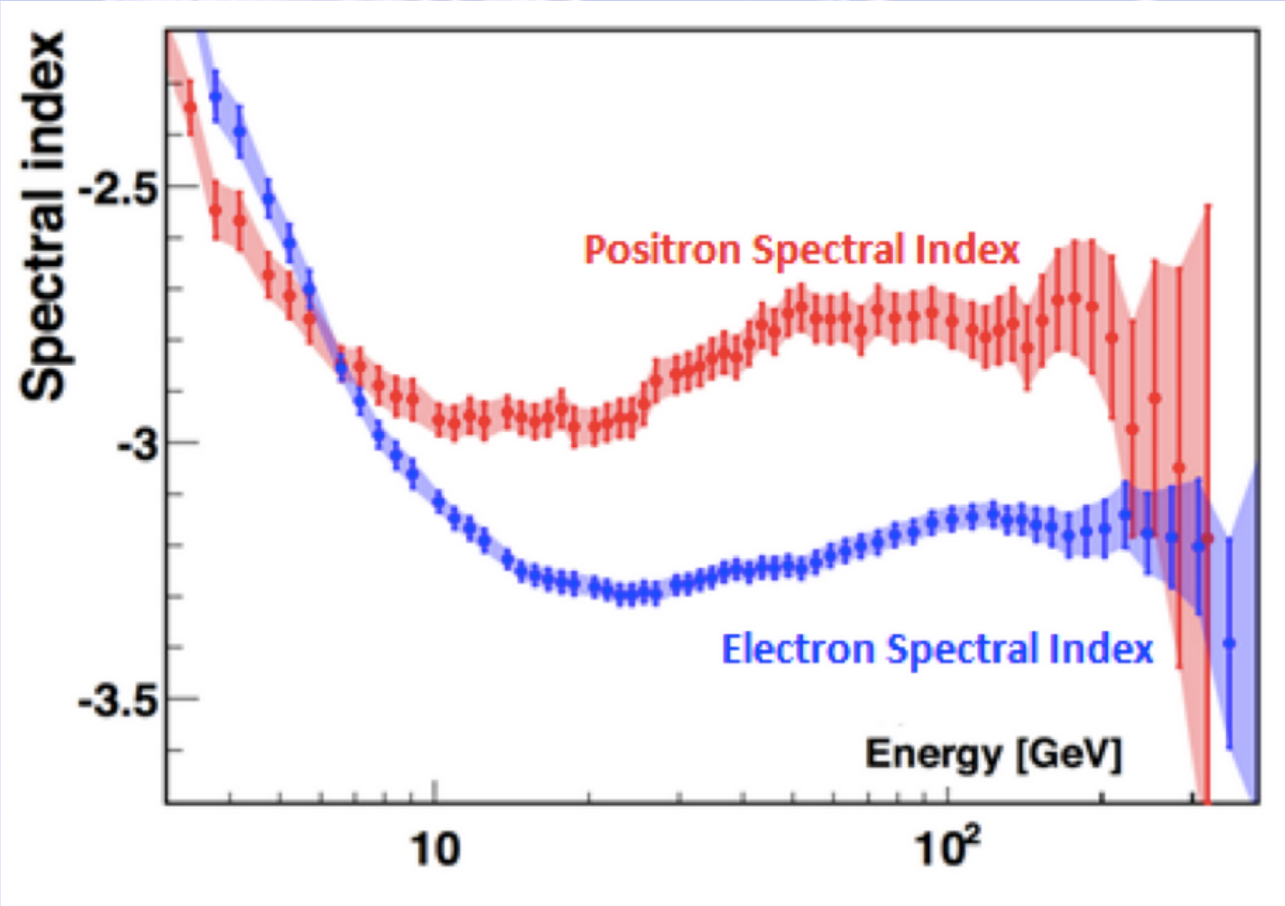
Frazione di positroni misurata da AMS-02
(Sett. 2014)

Flusso combinato $e^{\pm} \times E^3$ misurato da AMS (Sett. 2014)



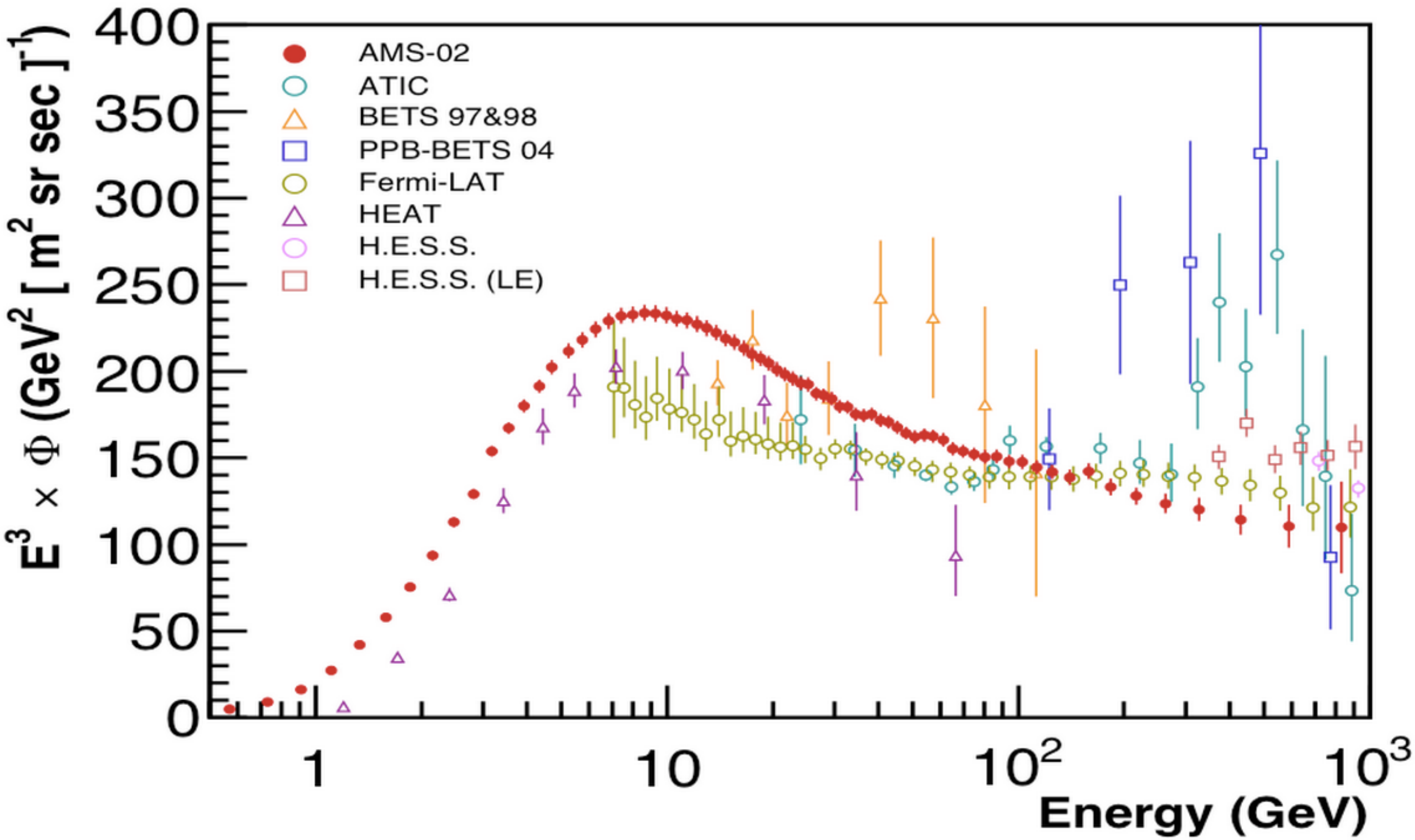


Flusso degli elettroni e dei positroni (Sett. 2014)

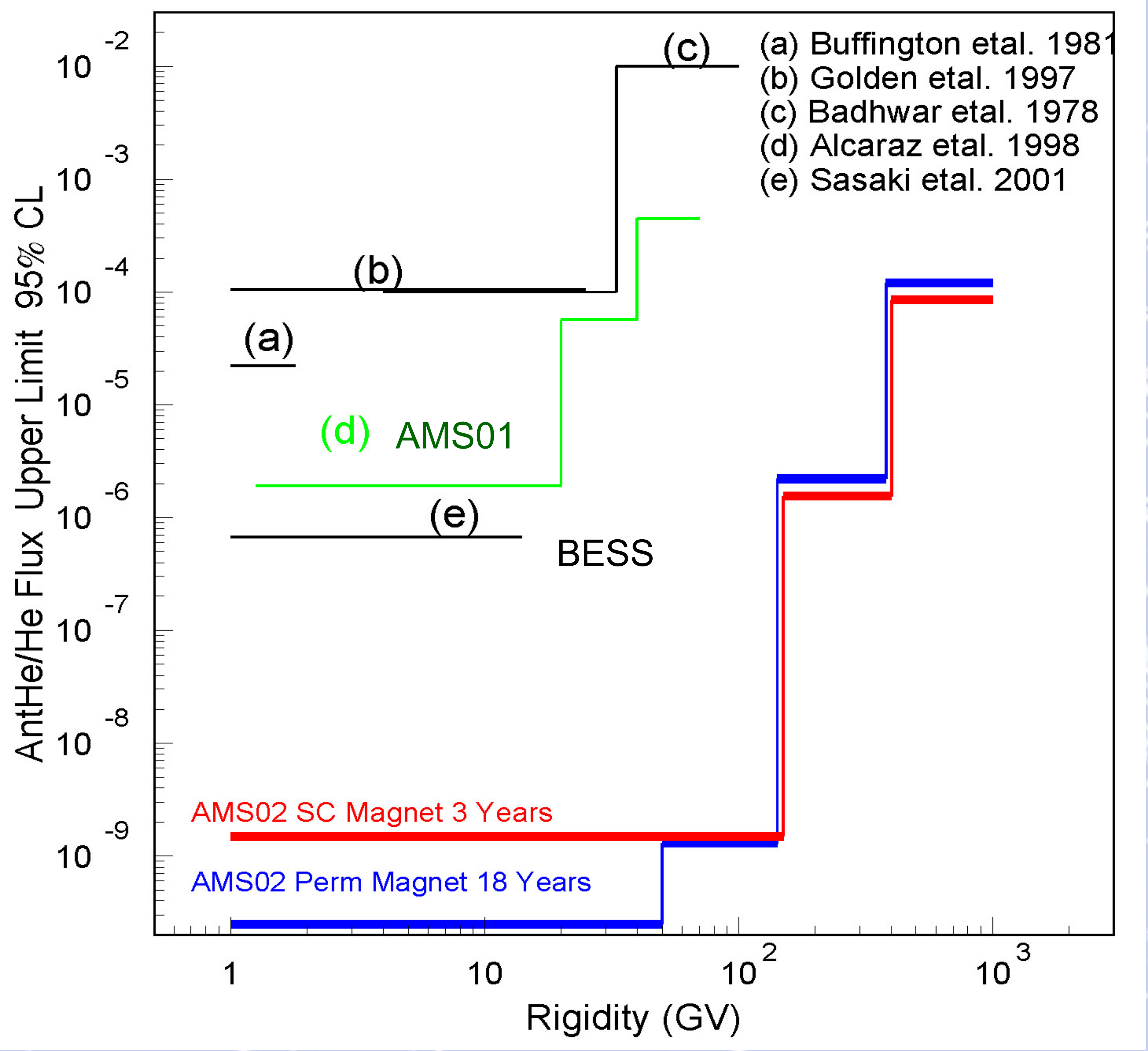


Indice spettrale degli elettroni e dei positroni (Sett. 2014)

Flusso combinato $e^{\pm} \times E^3$ misurato da AMS (Sett. 2014)



La fisica di AMS-02: ricerca di antimateria cosmica residua (limite sulla presenza di $\overline{He}$)

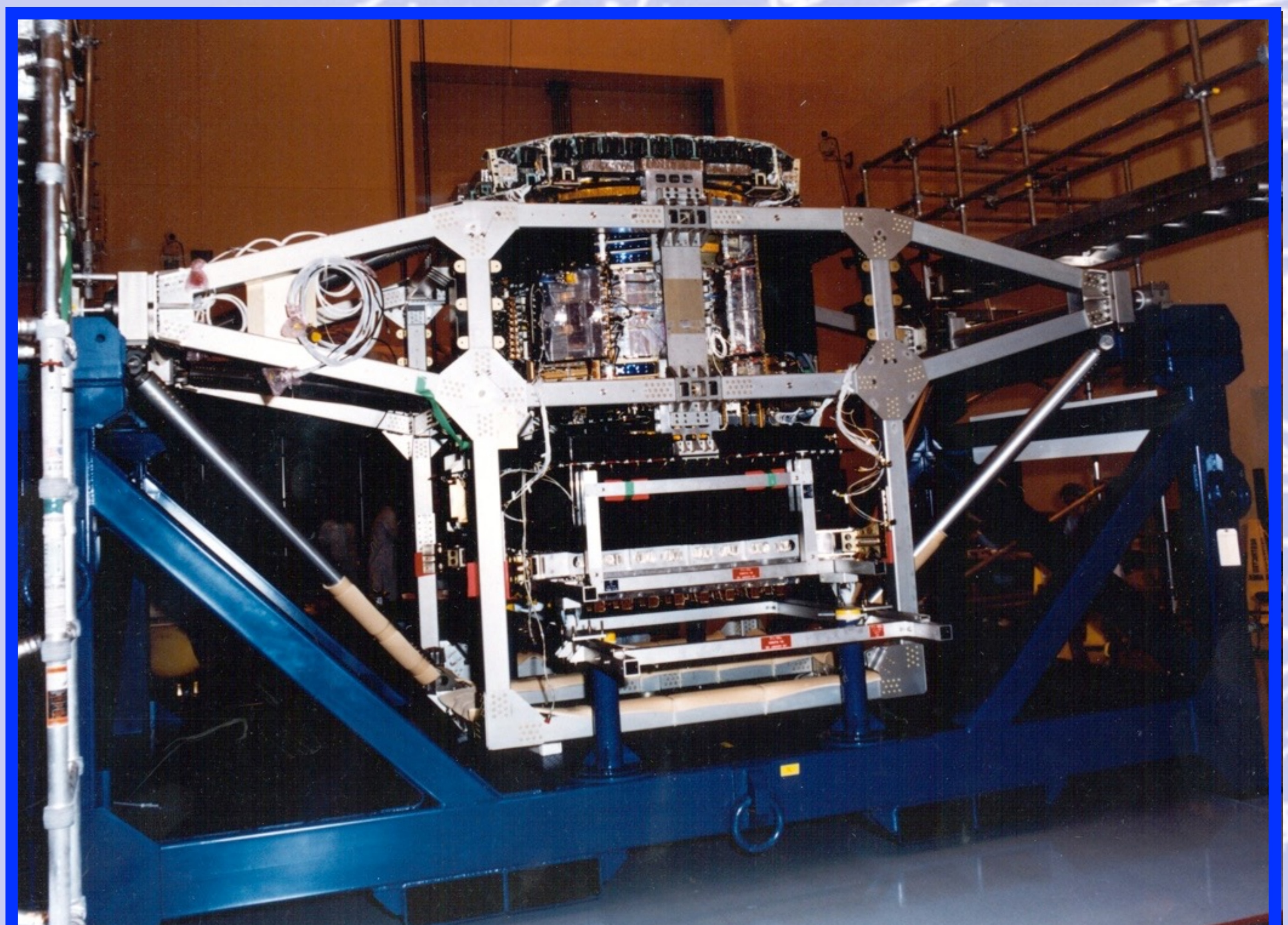


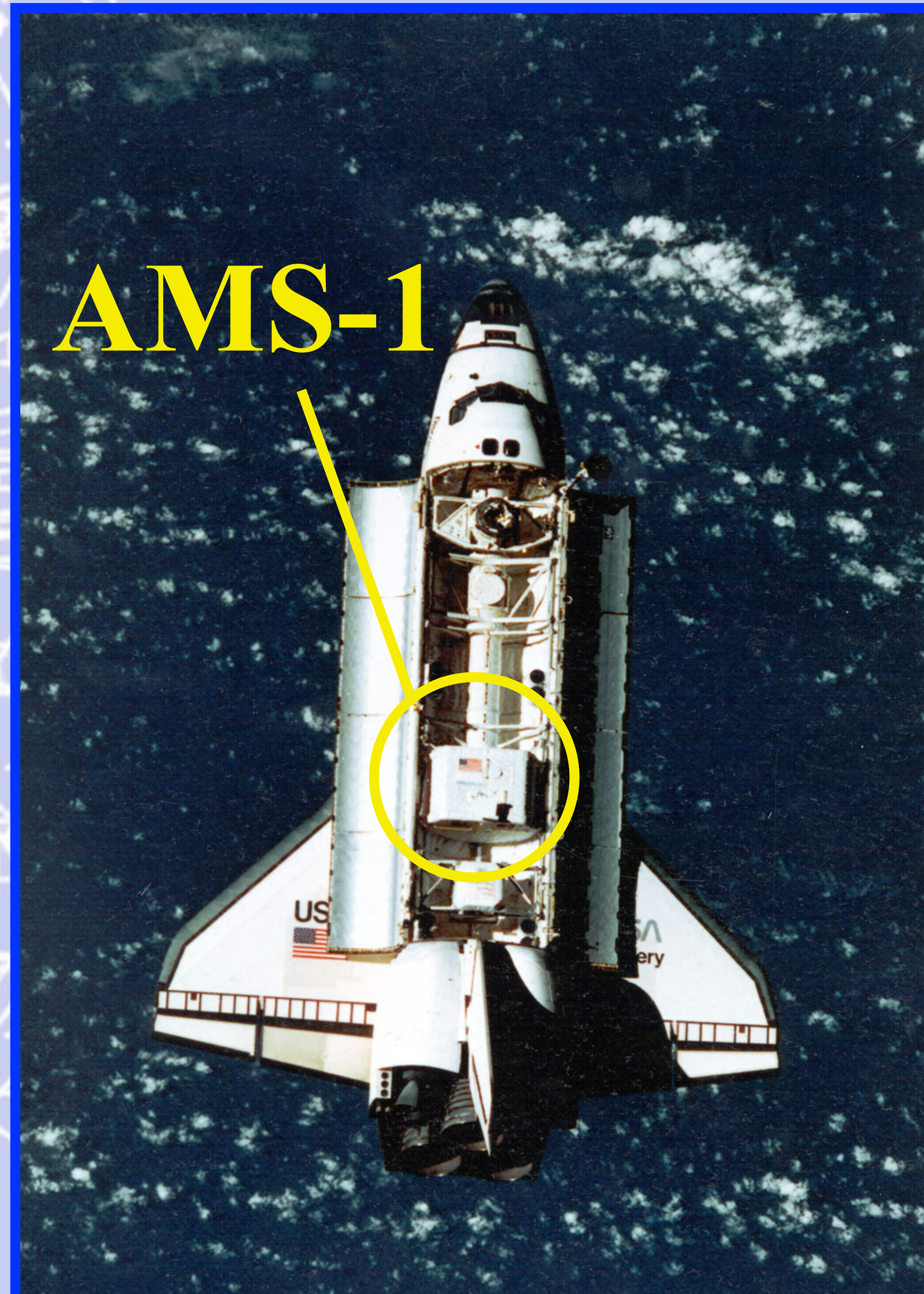
Appendice 14

(L’esperimento pilota AMS-01)

Experience from the AMS-1 flight (STS-91) 1998

- **Data taking ≈135 hours;**
- **Shuttle altitude ≈370 km;**
- **100 million events recorded.**

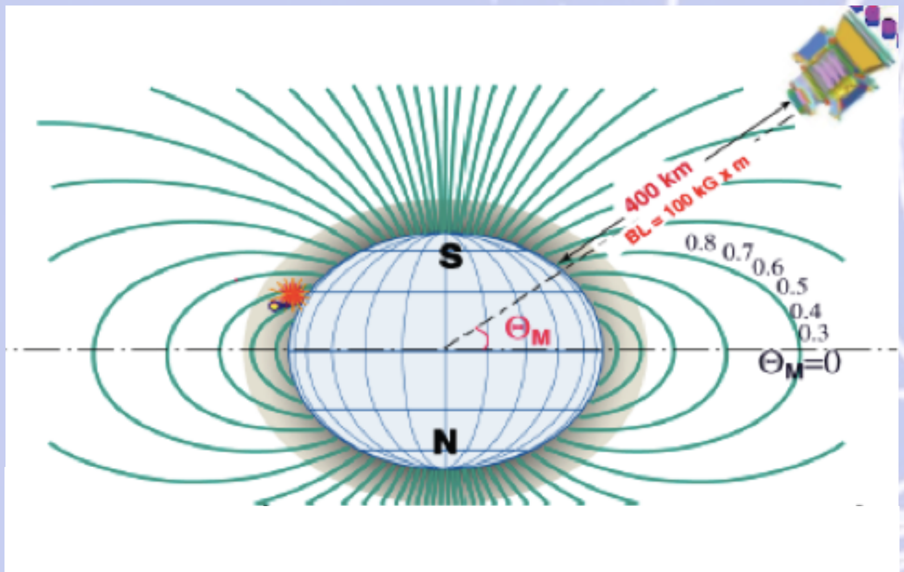


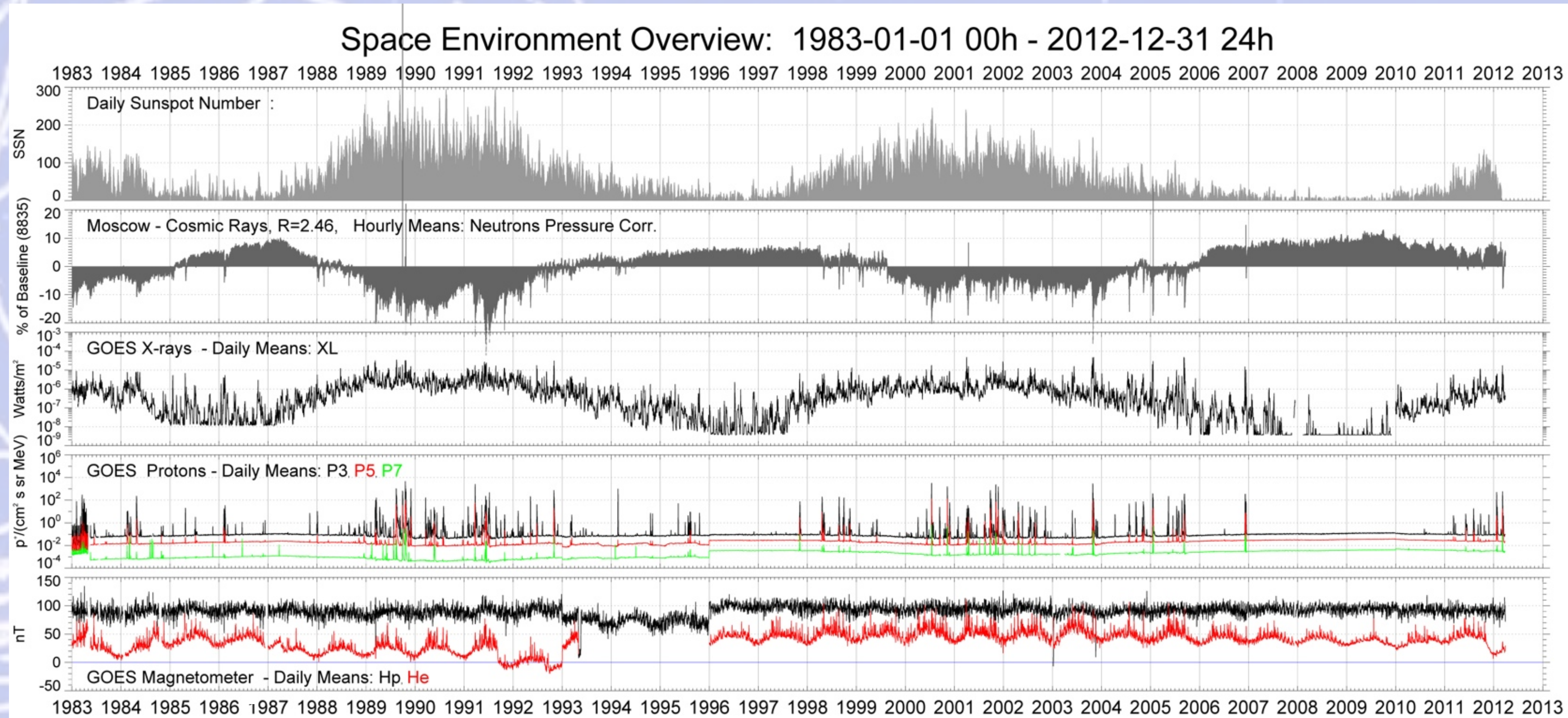


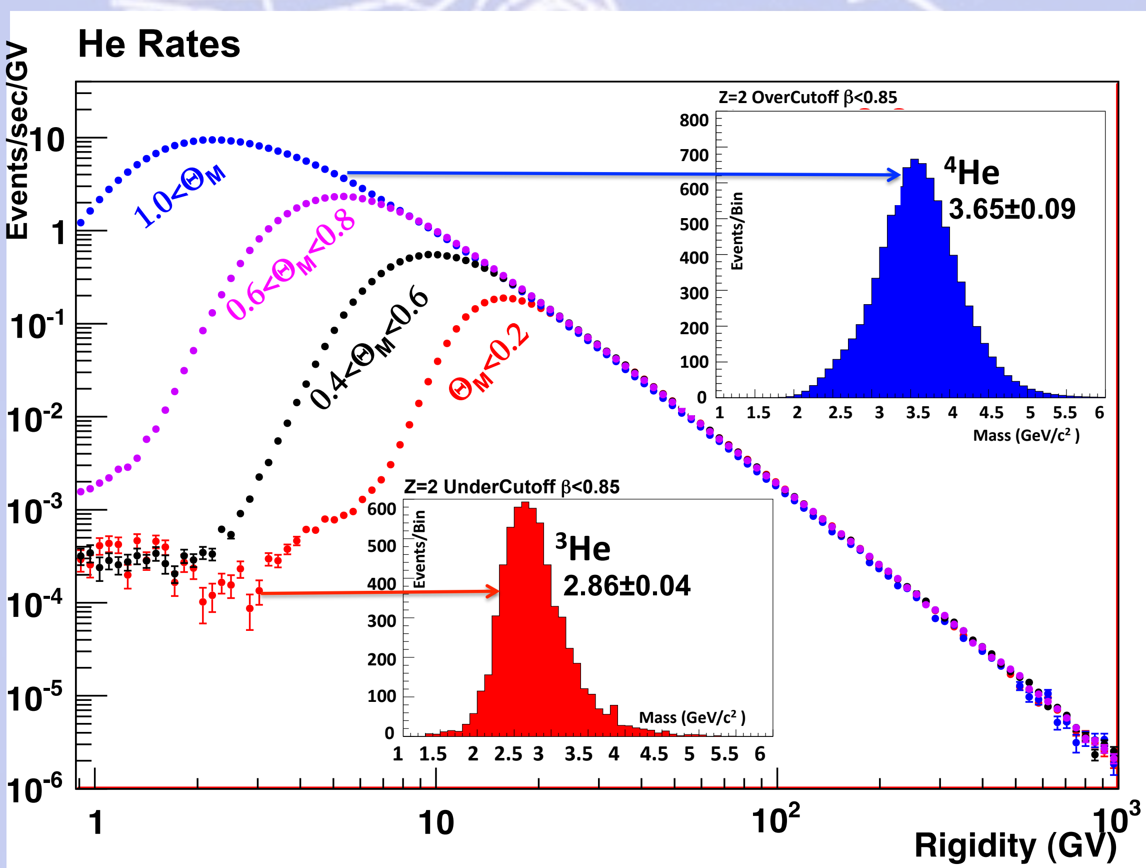
Appendice 15

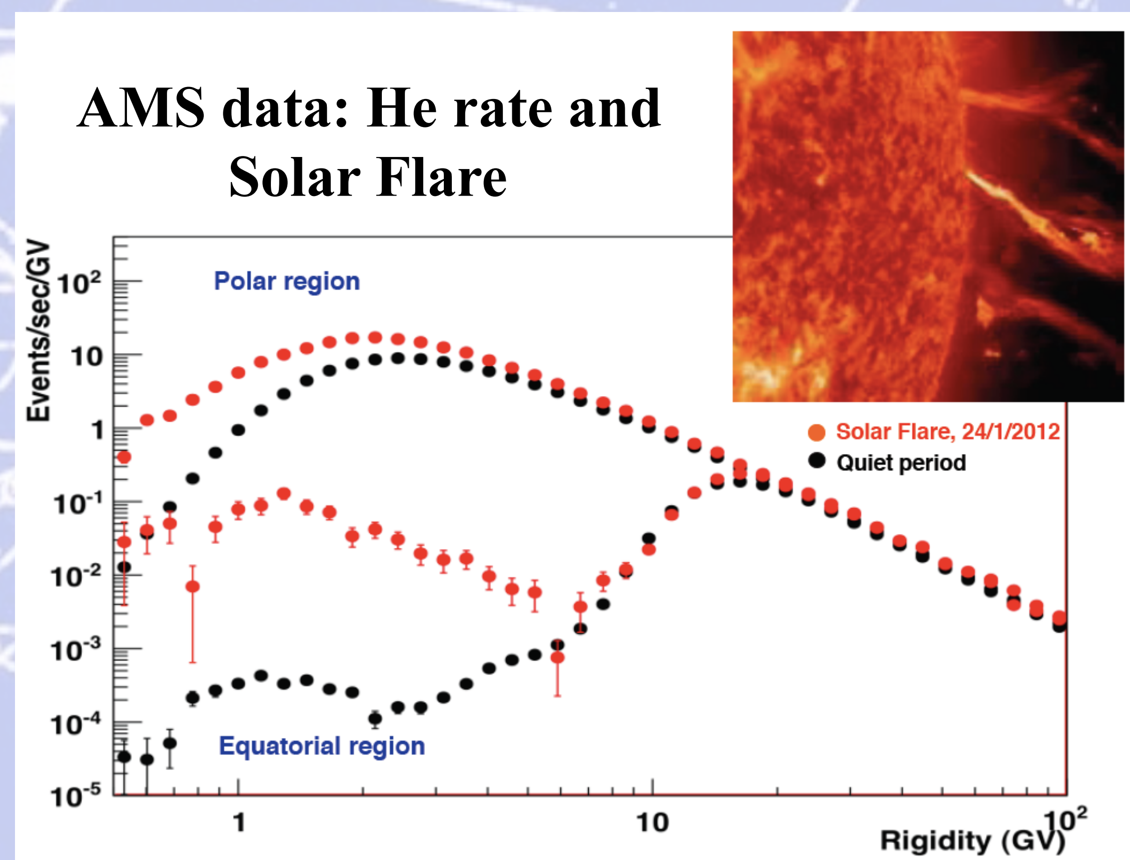
(Varie ed eventuali)

Data from AMS on ISS: He rate







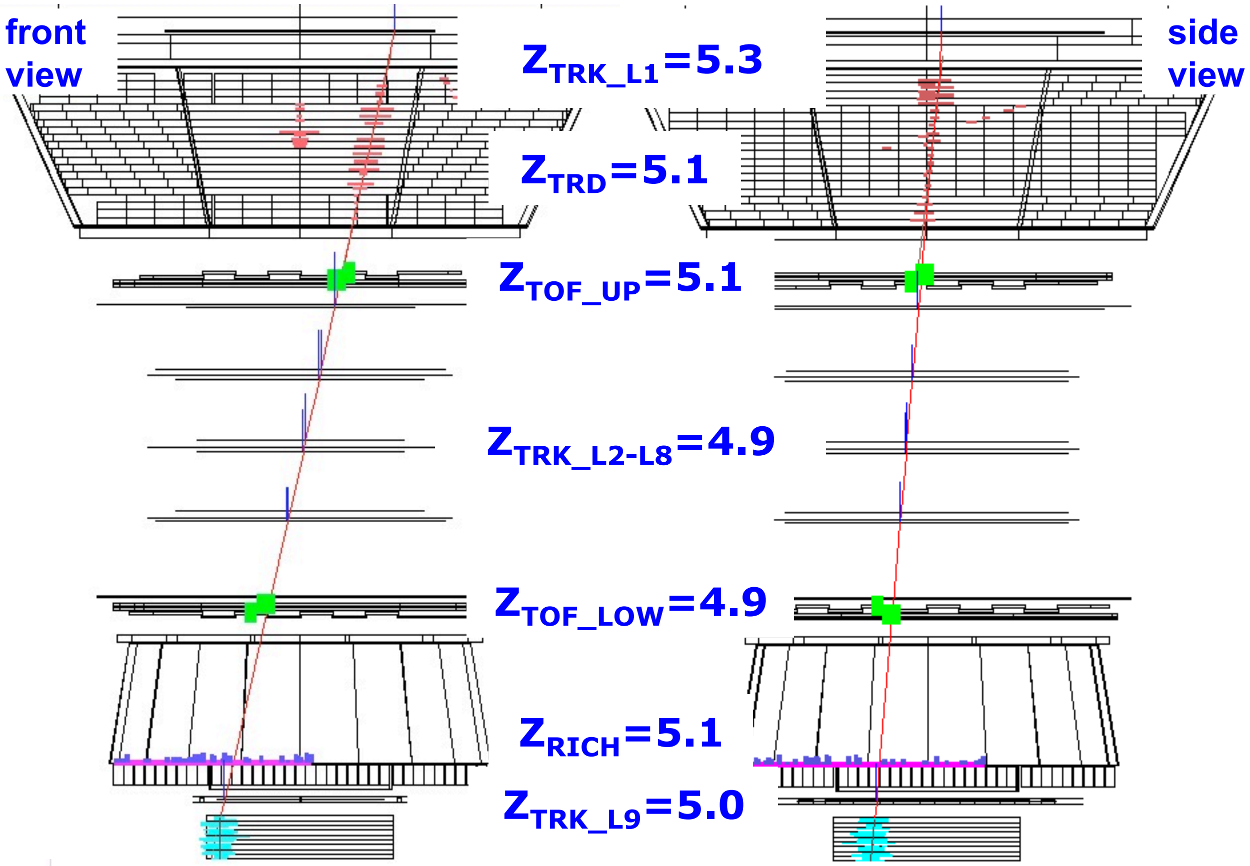


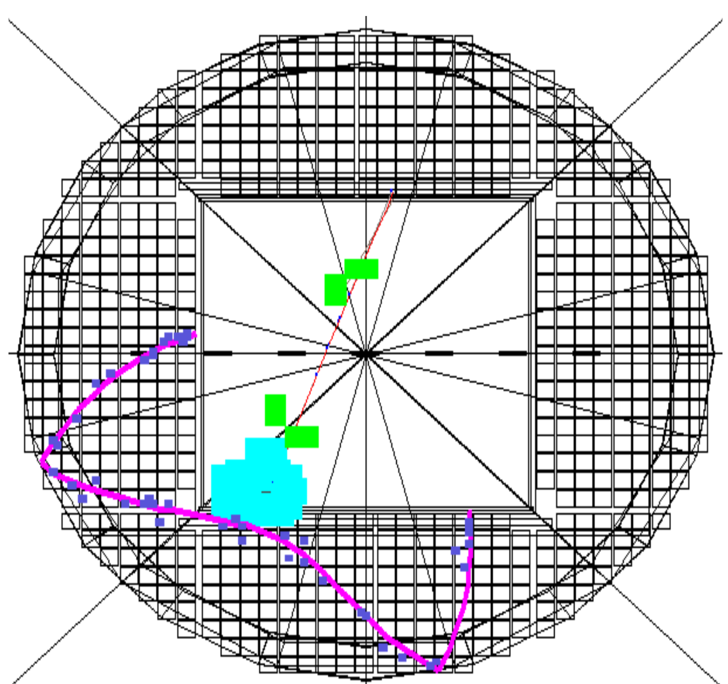
Rigidity ~ 3 GV

Boron

Rigidity=3.7 GV

Run/Event 1333501084/ 42231

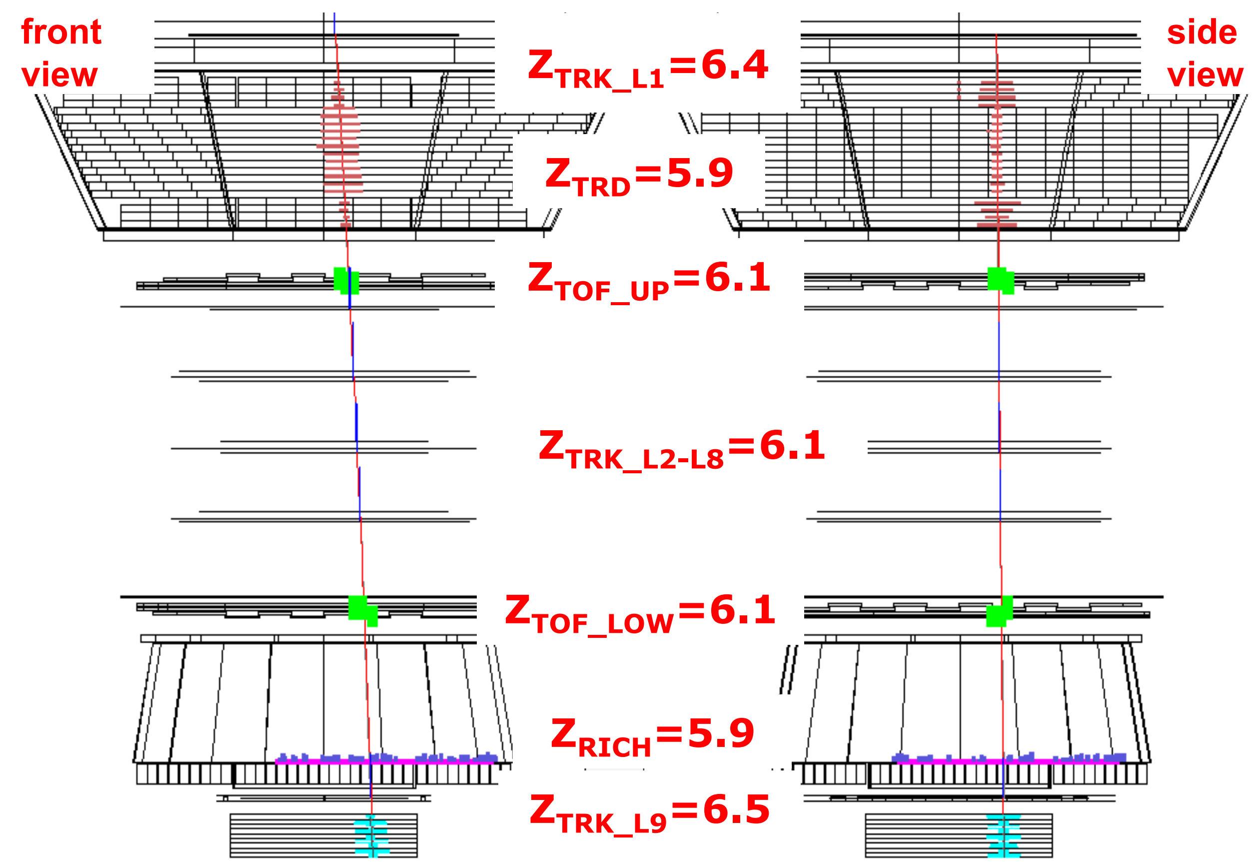


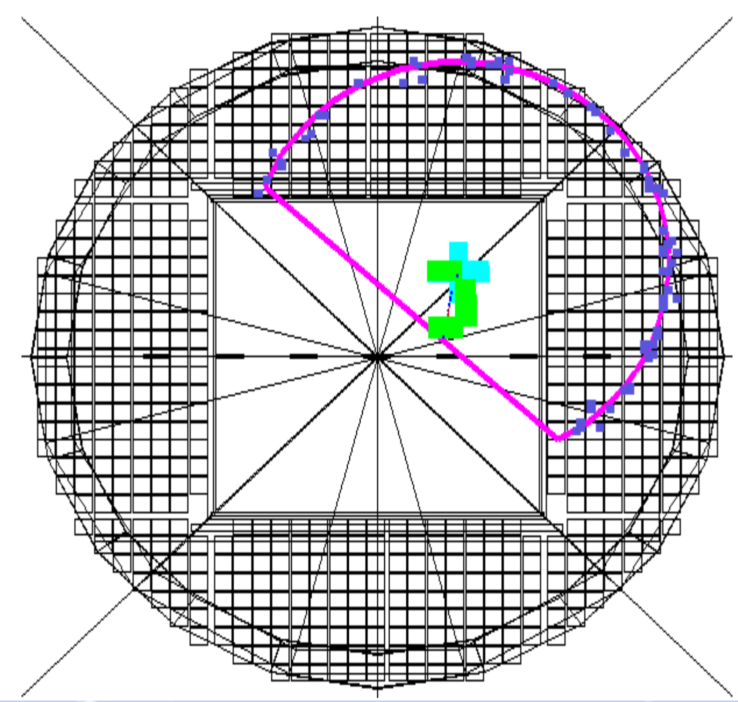


Carbon

Rigidity=3.3 GV

Run/Event 1327519853/ 487070

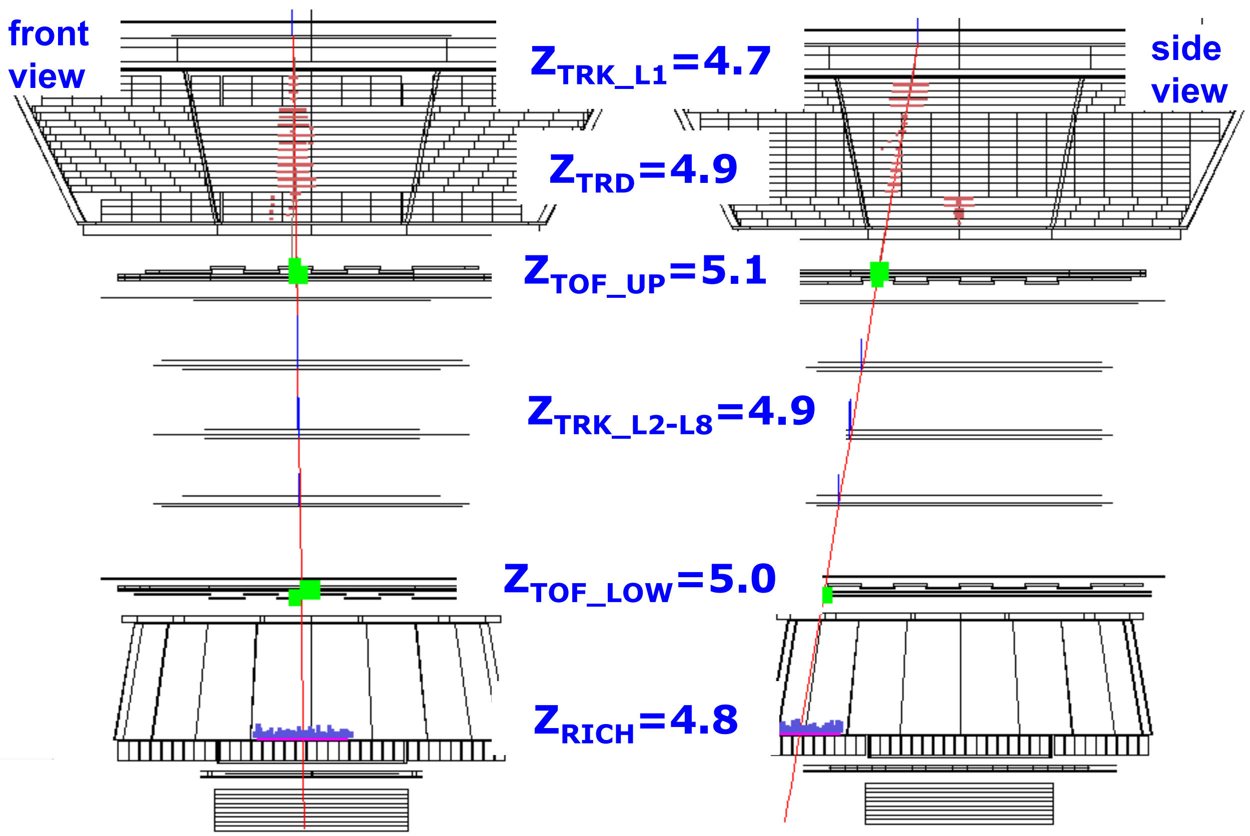




Rigidity ~ 20 GV

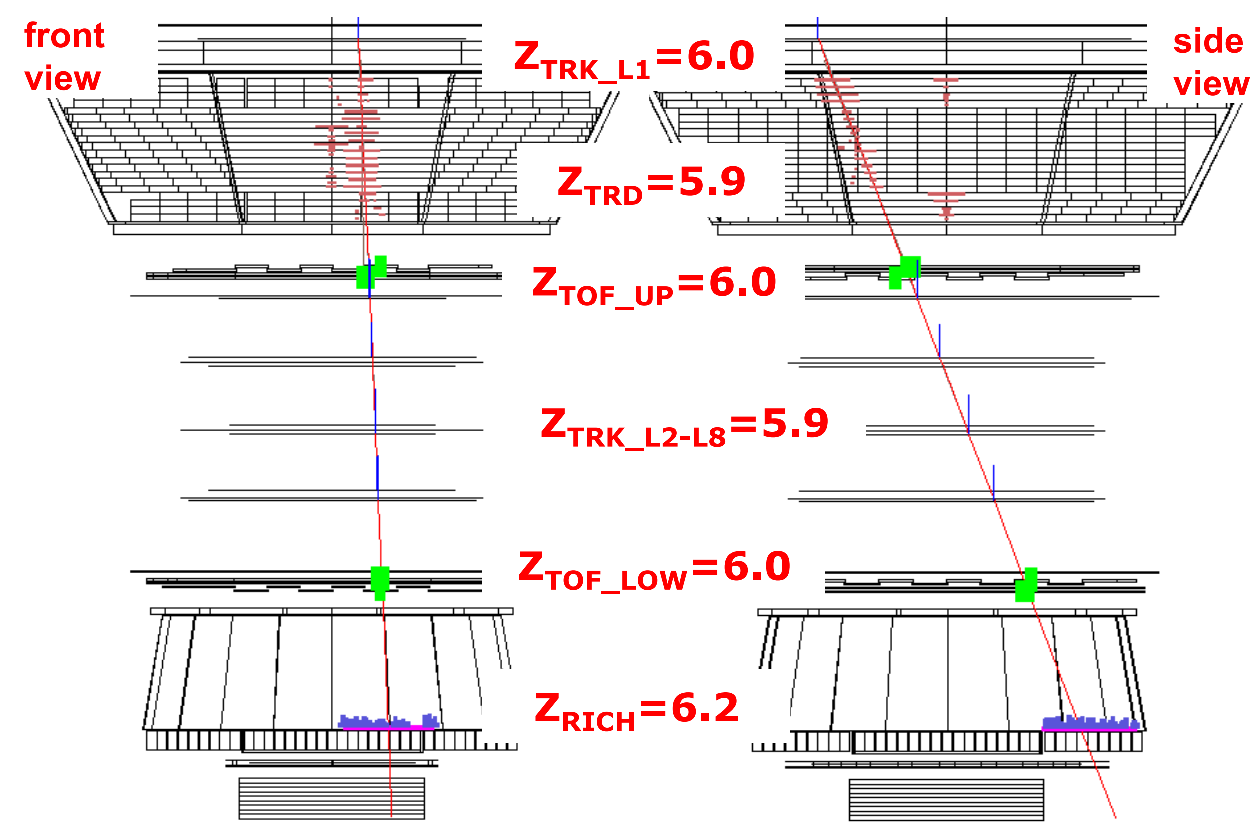
Boron
Rigidity=24 GV

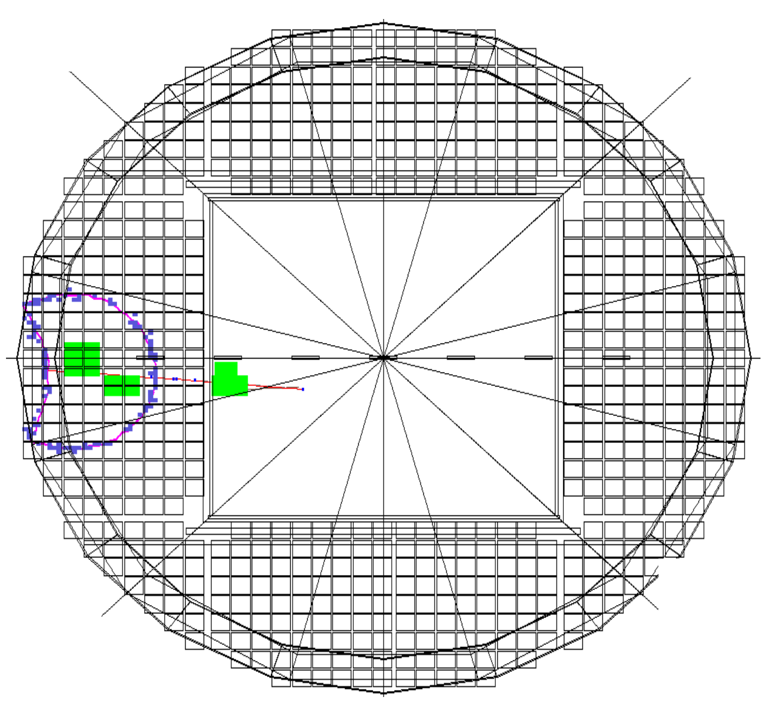
Run/Event 1326201809/ 798775

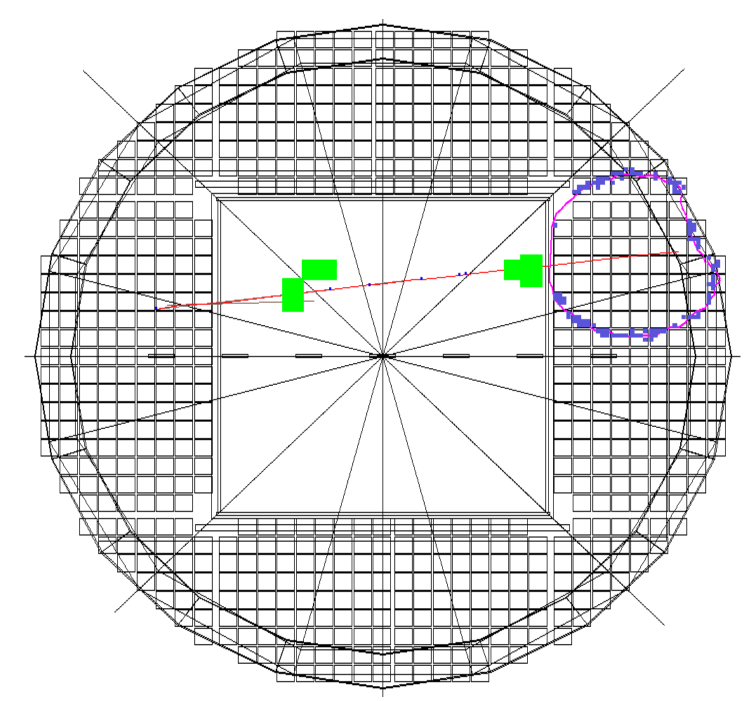


Carbon
Rigidity=24 GV

Run/Event 1329490720/ 473181





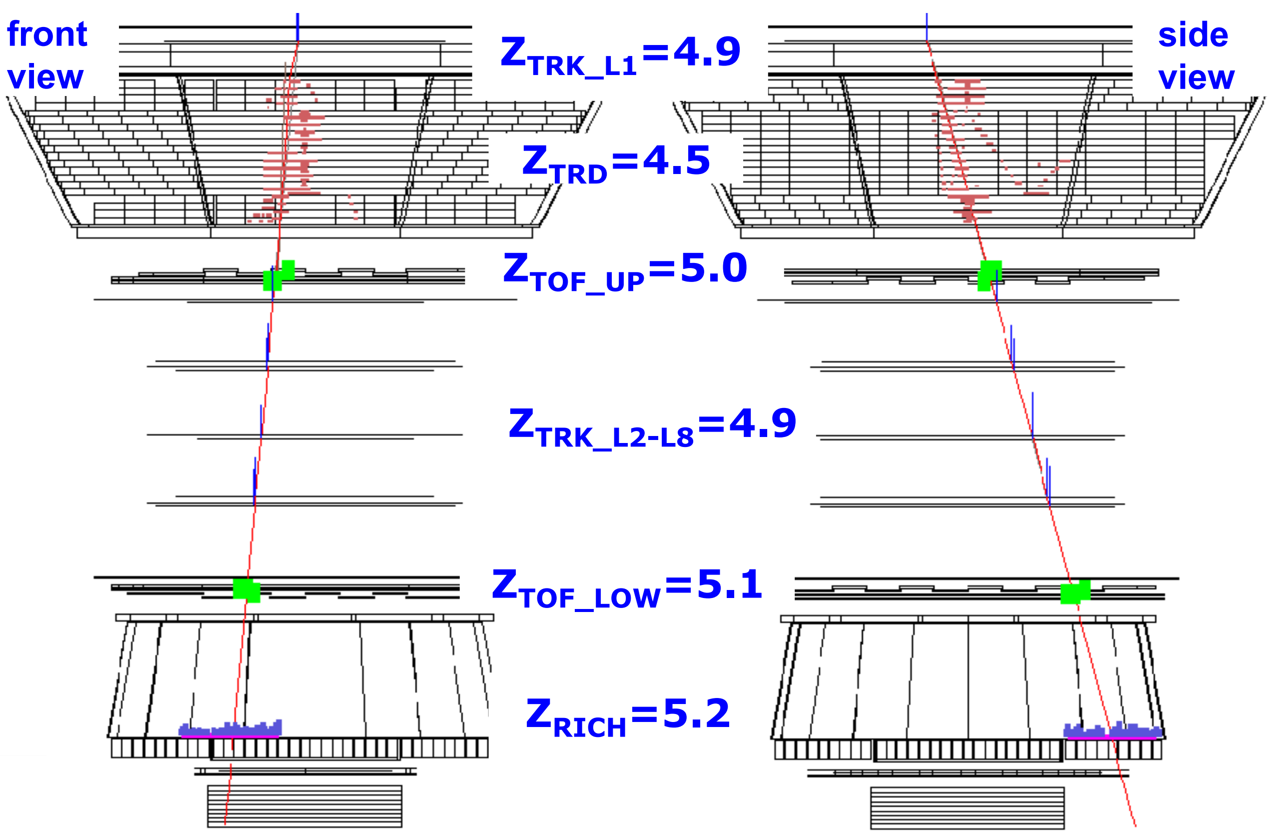


Rigidity ~ 200 GV

Boron

Rigidity=187 GV

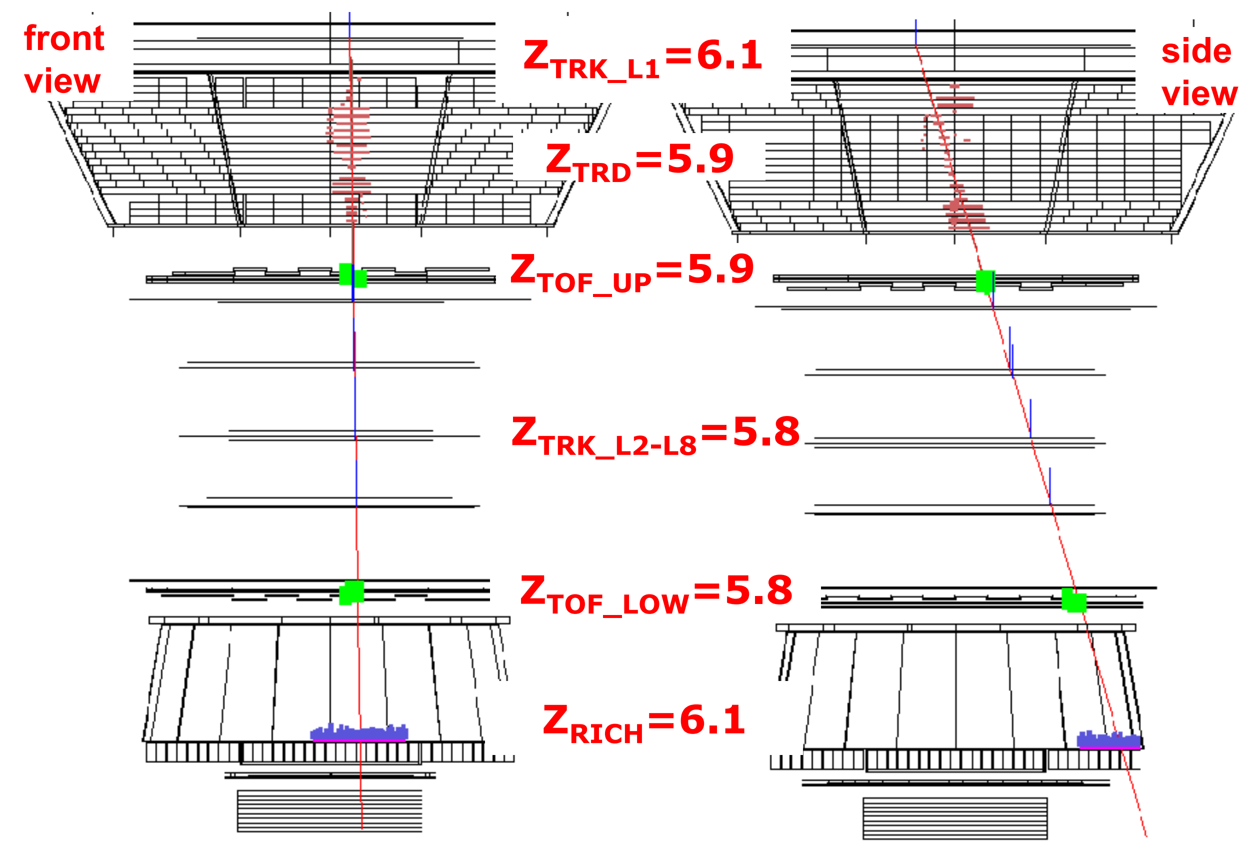
Run/Event 1329086299/ 747549

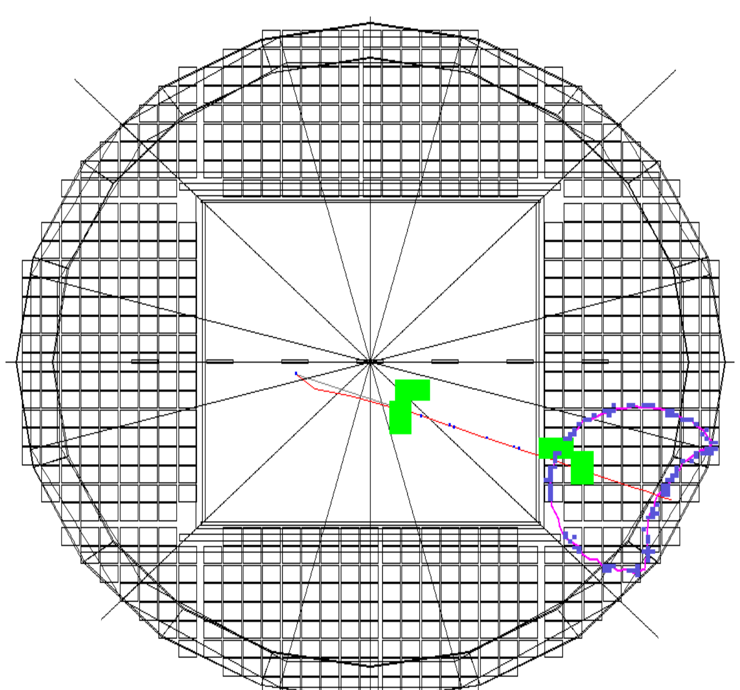


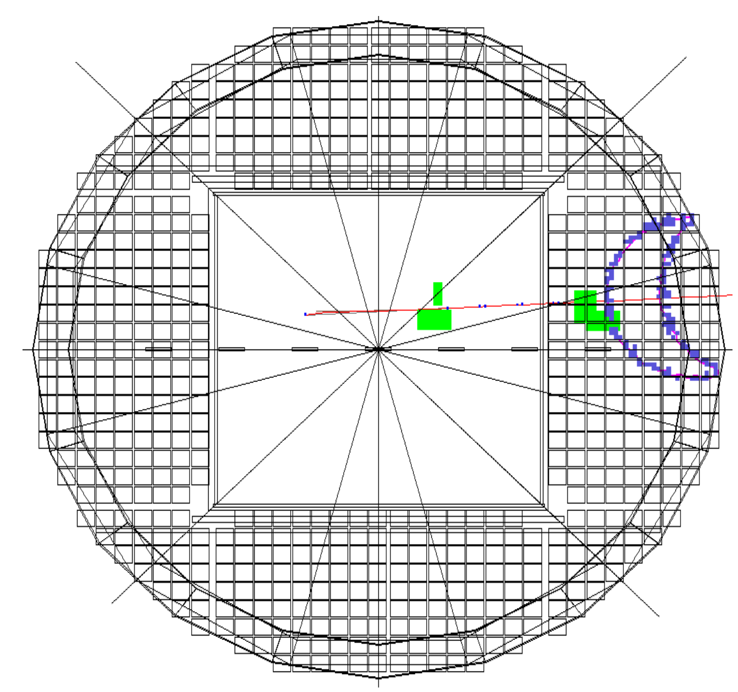
Carbon

Rigidity=215 GV

Run/Event 132643580/ 132197





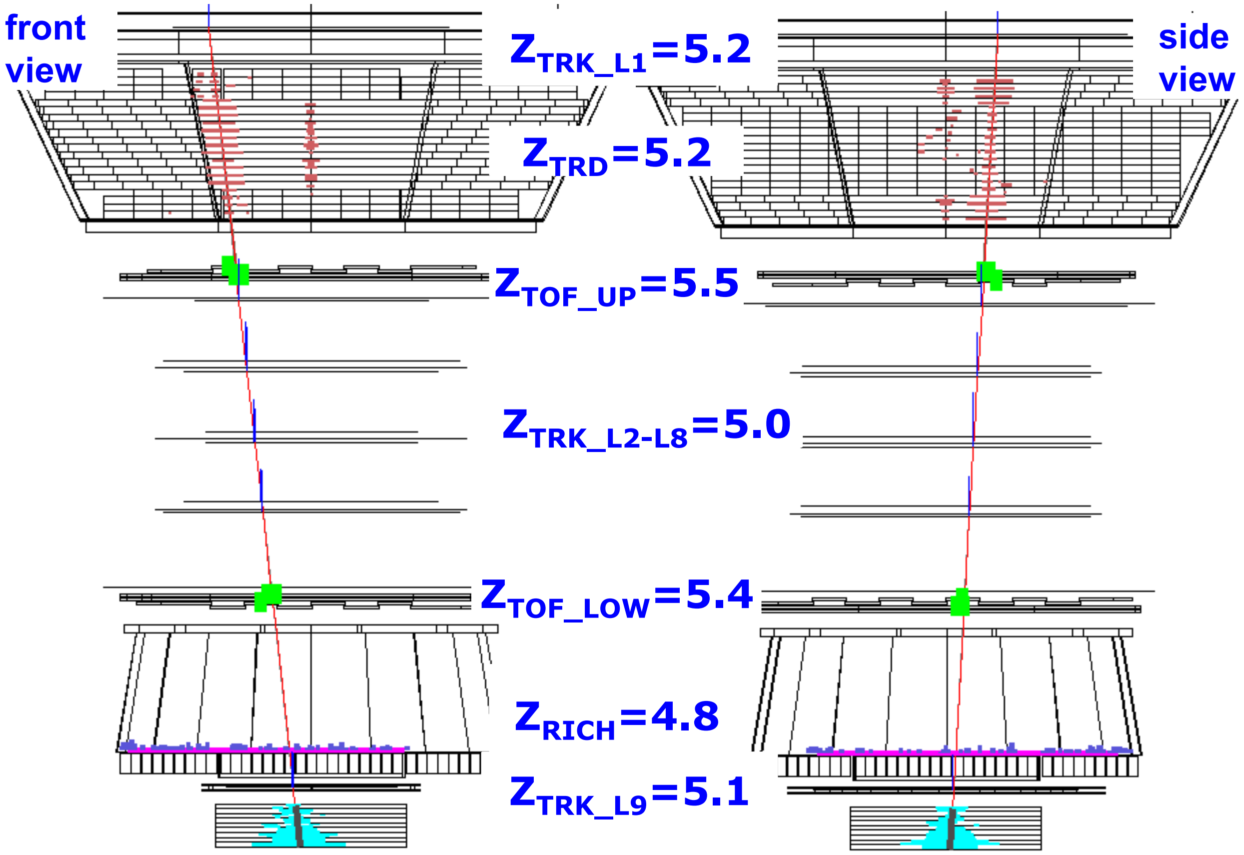


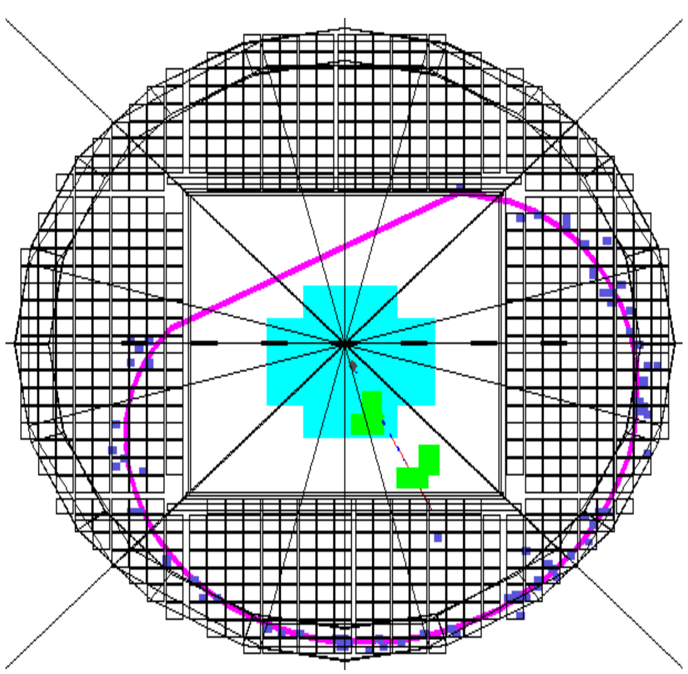
Rigidity ~ 700 GV

Boron

Rigidity=680 GV

Run/Event 1319990213/ 235892

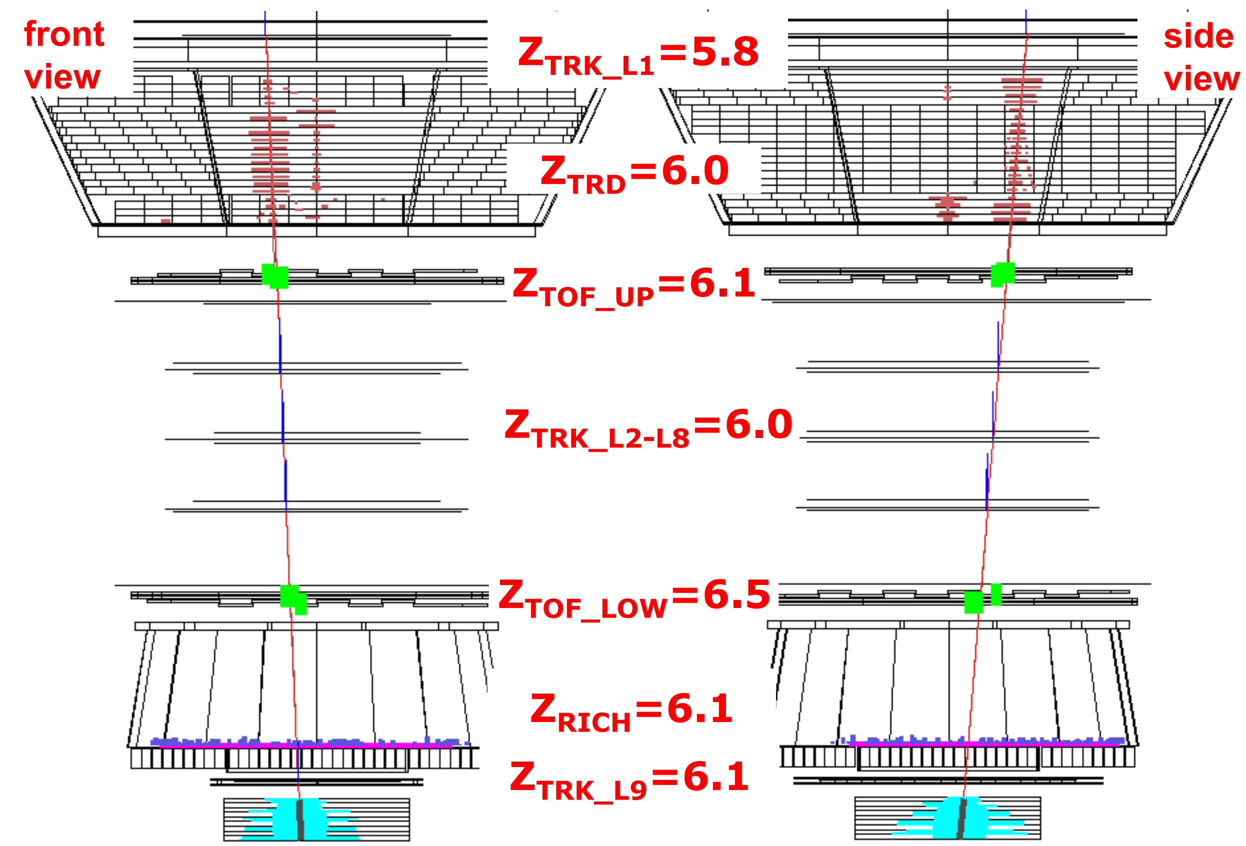


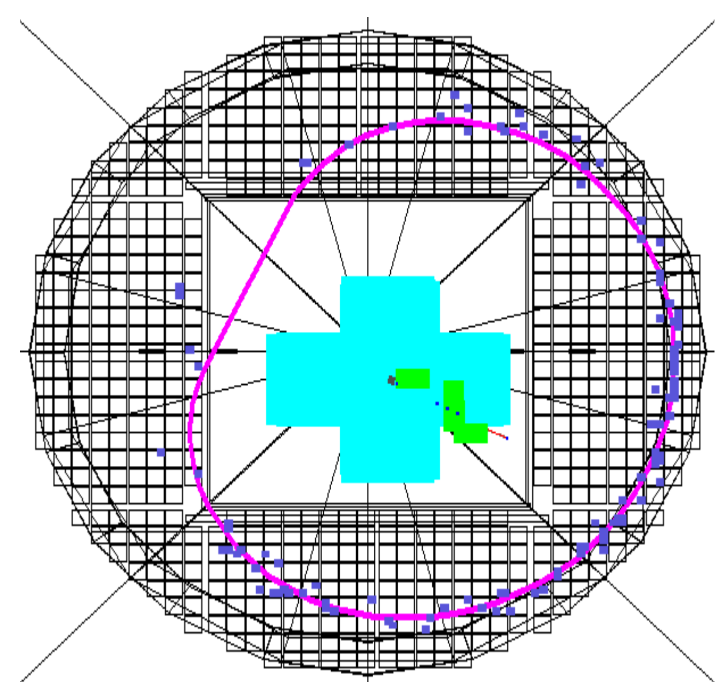


Carbon

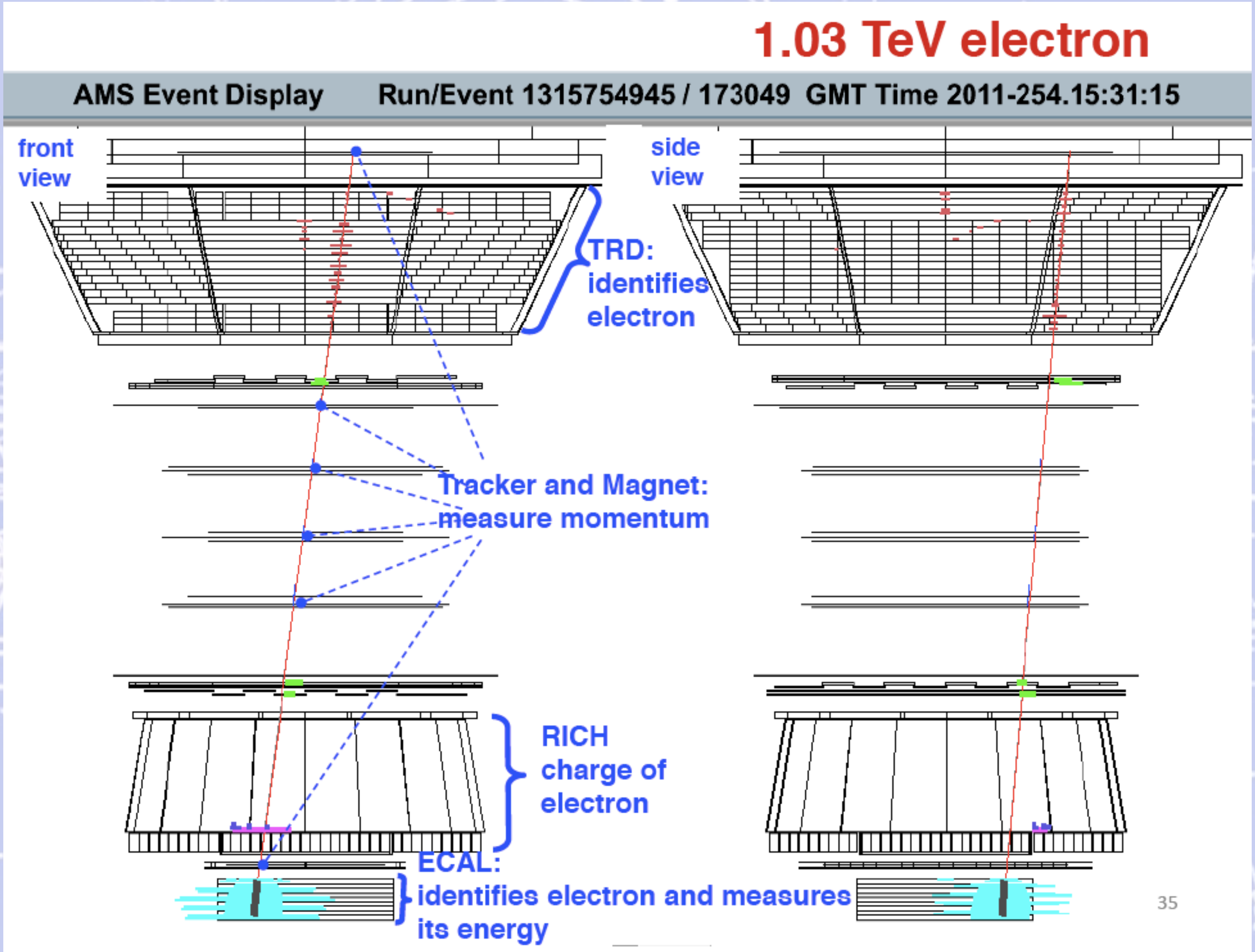
Rigidity=666 GV

Run/Event 1327184805/ 266043





AMS ISS data: electrons



AMS ISS data: positrons